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Top-down Methodology to Identify Opportunities for Industrial Symbiosis Partnerships

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ABSTRACT

Industries in Europe are responsible for generating approximately 190 Mtons of waste; a figure which is expected to rise, as a significant increase in the consumption of raw materials is predicted to occur in the near future. This may lead to escalating environmental problems, including resource depletion, soil degradation, and climate change. To curtail these problems, countries, regions, and industrial systems need to find ways to promote and foster Circular Economy strategies.

The promotion and implementation of Industrial Symbiosis (IS) partnerships is one of the strategies for implementation of Circular Economy concepts. IS has been recognized by the European Union as a tool that can be used to promote sustainable growth and resource efficiency, by enabling companies to use wastes, energy, or water generated by other companies as raw materials in their industrial processes.

In reality, however companies face numerous challenges when trying to find opportunities to engage in IS partnerships. One way to expand the opportunities for Industrial Symbiosis is by broadening its scope from eco-industrial parks to entire regions, by exploring the potential for using wastes already available in the region as raw materials. This may also reduce dependence on resource extraction and materials imported from other countries.

Bottom-up approaches are commonly used to identify opportunities for IS partnerships, and include tools like surveys and workshops. However, these approaches can be difficult to implement, primarily because of time and cost constraints. Fortunately, as it is now possible to collect large datasets, top-down approaches can be used to develop tools that facilitate identification of IS opportunities.

The aim of this thesis is to develop a top-down methodology for mapping IS opportunities and identifying potential stakeholders. Types of materials that can be reused and recycled are identified, as well as companies that may collaborate by sharing resources. The method can be applied at different spatial scales, from industrial parks to municipalities, regions, or countries. It employs routinely reported statistical data for industries, which enables simple data acquisition and ensures that any changes in the production processes are captured. It contains information on approximately 100 industries, 1,250 products, and 800 waste types.

The results show that currently available datasets can be used to identify IS opportunities, and that input materials and wastes generated by industries can be predicted. After matching inputs to wastes, a tool based on two databases was developed. This tool can be used to identify opportunities for IS partnerships within any region in Europe. The tool was tested in the Västra Götaland Region of Sweden, in three case studies: one for wood wastes, one for biogas, and another for carbon capture and utilization. The results can be used by regional development authorities or other institutions to support the establishment of IS partnerships.

Keywords: Industrial Symbiosis, Circular Economy, Recycling, Top-down methods, Industrial Waste, Material Inputs

LIST OF PUBLICATIONS

This Thesis was developed in the Urban Metabolism research group at Chalmers University, in the Water Environment Technology Division at the Department of Architecture and Civil Engineering. The research work was done under the supervision of Professor Yuliya Kalmykova and Assistant Professor Leonardo Rosado.

The research presented in this thesis was made under different research projects. Firstly, the "EnCO2re" (Enabling CO_2 reuse) project, which was a flagship project financed by the European Institute of Innovation and Technology – Climate Knowledge Innovation Community, that focused on all the aspects of a successful CCU scheme (EnCO2re, 2017). One of these aspects included industrial symbiosis as a tool to promote CO_2 utilization. Secondly, the Regional industrial symbiosis project financed by Business Region Gothenburg and Västra Götaland Region. This project aimed to develop methodologies that may help local stakeholders establishing and implementing regional industrial symbiosis projects within the Västra Götaland Region.

The research was funded by the European Institute of Innovation and Technology through Climate Knowledge Innovation Community, Business Region Göteborg and Västra Götaland Region.

The Ph.D thesis is based on the following appended papers:

Paper I: Patricio, J., Axelsson, L., Blomé, S., & Rosado, L. 2018. Enabling industrial symbiosis collaborations between SMEs from a regional perspective. *Journal of Cleaner Production*, **202**, pp.1120-1130. doi: 10.1016/j.jclepro.2018.07.230

Paper II: Patricio, J., Kalmykova, Y. and Rosado, L., 2020. A method and databases for estimating detailed industrial waste generation at different scales–With application to biogas industry development. *Journal of Cleaner Production*, **246**, p.118959. doi: 10.1016/j.jclepro.2019.118959

Paper III: Patricio, J., Jimenez Encarnacion, D., Kalmykova, Y. and Rosado, L., 2020. Top-down method and databases for typical product demands of 103 manufacturing industries. *Submitted to Journal of Resources Conservation & Recycling* (under review)

Paper IV: Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y. and Rosado, L., 2017. Method to identify opportunities for CCU at regional level—Matching sources and receivers. *Journal of CO2 Utilization*, **22**, pp.330-345. doi: 10.1016/j.jcou.2017.10.009

Paper V: Patricio, J., Kalmykova, Y., Rosado, L., Cohen, J., Westin, A. and Gil, J. 2020. Top-down method to support the identification of potential opportunities for industrial symbiosis partnerships. *Manuscript*

Other papers that were authored or co-authored during the realization of this Ph.D Thesis are listed below, which are not appended to the Thesis:

Patricio, J., Angelis-Dimakis, A., Castillo-Castillo, A., Kalmykova, Y. and Rosado, L., 2017. Region prioritization for the development of carbon capture and utilization technologies. *Journal of CO2 Utilization*, **17**, pp.50-59. doi: 10.1016/j.jcou.2016.10.002

Kalmykova, Y., Berg, P.E.O., Patrício, J. and Lisovskaja, V., 2017. Portable battery lifespans and new estimation method for battery collection rate based on a lifespan modeling approach. *Resources, Conservation and Recycling*, **120**, pp.65-74. doi: 10.1016/j.resconrec.2017.01.006

Rosado, L., Kalmykova, Y. and Patrício, J., 2016. Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. *Journal of Cleaner Production*, **126**, pp.206-217. doi: 10.1016/j.jclepro.2016.02.139

Kalmykova, Y., Rosado, L. and Patrício, J., 2016. Resource consumption drivers and pathways to reduction: economy, policy and lifestyle impact on material flows at the national and urban scale. *Journal of Cleaner Production*, **132**, pp.70-80. doi: 10.1016/j.jclepro.2015.02.027

Patrício, J., Kalmykova, Y., Rosado, L. and Lisovskaja, V., 2015. Uncertainty in material flow analysis indicators at different spatial levels. *Journal of Industrial Ecology*, **19(5)**, pp.837-852. doi: 10.1111/jiec.12336

Patrício, J., Kalmykova, Y., Berg, P.E., Rosado, L. and Åberg, H., 2015. Primary and secondary battery consumption trends in Sweden 1996–2013: Method development and detailed accounting by battery type. *Waste Management*, **39**, pp.236-245. doi: 10.1016/j.wasman.2015.02.008

Kalmykova, Y., Rosado, L. and Patrício, J., 2015. Urban economies resource productivity and decoupling: Metabolism trends of 1996–2011 in Sweden, Stockholm, and Gothenburg. *Environmental Science & Technology*, **49(14)**, pp.8815-8823. doi: 10.1021/acs.est.5b01431

Kalmykova, Y., Patrício, J., Rosado, L. and Berg, P.E., 2015. Out with the old, out with the new–The effect of transitions in TVs and monitors technology on consumption and WEEE generation in Sweden 1996–2014. *Waste Management*, **46**, pp.511-522. doi: 10.1016/j.wasman.2015.08.034

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LIST OF ABBREVIATIONS

The following notations are used in the main text of the thesis:

CCU	Carbon Capture and Utilization
CE	Circular Economy
CO_2	Carbon Dioxide
CN	Combined Nomenclature
EU	European Union
EWC-stat	European Waste Classification for Statistics
GHG	Greenhouse Gases
GIS	Geographic Information Systems
IS	Industrial Symbiosis
IWR	Industry Waste Ratio
LCA	Life-Cycle Assessment
LoW	Nomenclature for the List of Wastes
MFA	Material Flow Accounting
Mt = Million tonnes	1.000.000.000 kg. In this study tonne stand for metric tonnes
NACE	Statistical Classification of Economic Activities in the European Community
NISP	National Industrial Symbiosis Program
OECD	Organisation for Economic Co-operation and Development
SCB	Statistics Sweden
SME	Micro, small and medium-sized enterprises
SMGs	Sustainable Development Goals
SWR	Sector Waste Ratio
TRL	Technology Readiness Level
WF	Waste Factor

1 INTRODUCTION

The industrial revolution had a clear positive impact on the standard of living of the human population. In parallel with the improved standard of living, the global population grew, leading to a significant increase in resource use. Data on the global extraction of materials show a fourfold increase; from 27.1 gigatons in 1970 to 92.1 gigatons in 2017 (UNEP, 2018). This rise in resource use led to increased generation of waste and emissions, as well as direct impacts on the natural environment (Saidani, 2018). Resource depletion, soil degradation, and climate change are some examples of associated environmental problems.

According to a forecast by the Organisation for Economic Co-operation and Development (OECD), the use of raw materials is expected to rise to 167 gigatons in 2060 (OECD, 2019). With continuously increasing production volumes, the generation of industrial waste is likely to increase significantly. According to Eurostat data from 2016 for the EU28 countries, 191.1 Mtons of waste was generated by the manufacturing industry alone (not including mineral wastes) (Eurostat, 2019). This shows that there is a need to change and adjust the current industrial structures, and to find better solutions, for example by increasing the efficiency of waste management (Tu et al., 2011; Yuan et al., 2006).

The United Nations has adopted 17 interconnected Sustainable Development Goals (SDGs), intended to "stimulate action over the next 15 years in areas of critical importance for humanity and the planet" (United Nations, 2019). The goals have been designed to balance the three dimensions of sustainable development. Goal 9 of the SDGs relates to the need to foster innovation and promote sustainable industrialization. This can be achieved by enhancing scientific research, upgrading technologies, and development of resilient manufacturing infrastructures (United Nations, 2019).

Meanwhile, we are facing the emergence of the so-called Fourth Industrial Revolution (Industry 4.0), which relies on the development of completely automated and intelligent production processes (Piccarozzi et al., 2018). A possible way to achieve this is to create and explore big-data sources. However, simply collecting the data is not sufficient; it is also necessary to obtain value out of it (Ardolino et al., 2018). It may be possible to use data-driven analysis to optimize sustainable solutions, including to make the use of resources and energy more efficient (Reis and Kenett, 2018; Tseng et al., 2018).

Over the last decade, the idea of recirculating materials rather than continuing to extract more raw materials has gained a lot of attention, as a way to help addressing the problems of resource overuse and environmental degradation. The Circular Economy (CE) concept is an emerging field that may enable improved resource utilization. The concept is complex and still under development, as shown in several studies (Kalmykova et al., 2018; Kirchherr et al., 2017). (Kirchherr et al., 2017) analyzed a set of 114 Circular Economy definitions. In this thesis, CE is defined as "an economic system that replaces the end-of-life concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation, and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers." (Kirchherr et al., 2017).

The successful implementation of Circular Economy concepts requires the involvement and collaboration of a number of different stakeholders, including industries, policy makers, etc. (Selman, 2000). It is essential that stakeholders have access to tools and studies that can facilitate the decision-making process and identify approaches that effectively promote waste circularity (Winans et al., 2017). Industrial Symbiosis (IS) is one of the three main fields within the Circular Economy arena. IS, in combination with eco-industrial parks and supply chains, has the ability to support sustainable industrialization (Homrich et al., 2018). Industrial Symbiosis can be defined as the sharing of resources between companies; this can include physical exchanges of materials, energy, water, and by-products among diversified clusters of companies (Chertow, 2007). The basic philosophy is to support the emergence of an industrial system relying on co-operation between the actors involved, in which they use each other's waste materials and energy as resources, and minimize both the input of virgin materials and energy into the system, and the output of waste products and emissions (Korhonen, 2001).

In recent years, IS has gradually been recognized by the European Union as a tool that can be used to promote sustainable growth and resource efficiency. In 2012, IS was defined as one of the top seven priority areas by the European Resource Efficiency Platform (Johnsen et al., 2015). More recently, the European Union adopted an ambitious package to promote Circular Economy, aimed at fostering sustainable industrial economic growth and generating new jobs. To achieve this, an action plan was drawn up, establishing several measures within the life cycle of a product, from the production phase to waste management. The plan sets clear targets for waste reduction, and includes concrete measures to be put in place to promote re-use and stimulate IS synergies (European Commission, 2017).

There are a number of known examples of implemented IS partnerships, including exchanges between industries located in industrial parks, however an eco-industrial park is limited by the borders of a single industrial agglomeration (Petríková et al., 2016). When considering a larger area, spontaneous emergence of IS partnerships between companies which are not co-located is less likely to happen, mostly due to limited information flows, a lack of understanding of the opportunities offered by IS, or a lack of know-how and resources relating to IS implementation (European Commission, 2018). Although recognized tools and programs that partly cover the mentioned challenges are available, there is still a need to develop more systematic methodologies. This includes comprehensive methods using standard nomenclatures, as well as match-making tools able to overcome informational barriers.

There are various ways to identify opportunities for IS partnerships, including new process discovery, input-output matching, georeferencing and GIS, case study mimicking, stakeholders' processes or materials budgeting (Grant et al., 2010). The so-called "top-down" methods can provide important support for these methods, allowing for instance the identification of companies' inputs and outputs (Song et al. (2017). Top-down methods use available statistical data, or other data sources, to describe and analyze a system or a specific problem. They have been applied to calculate material stocks, set up economic input–output tables, account for lifetime distributions of end-use products (Hirato et al., 2009), and to compute detailed information on consumption in the manufacturing sector (Roibás et al., 2017). When compared to ”bottom-up” approaches, top-down methods have some advantages, including that they can be applied to various spatial and temporal datasets; consider the entire system; and may be less labor and time intensive. Nevertheless, these methods also have some known limitations, including higher levels of uncertainty, a need for complex data analysis, and the need for more general assumptions (Jiang et al., 2014).

1.1 Aim and research questions

The aim of this thesis has been to advance methods for identification of potential industrial symbiosis partnerships at a regional level. In order to achieve the aim of the study, this thesis has been designed to answer the following research questions:

RQ 1: Which challenges do companies face to become a partner of an Industrial Symbiosis?

RQ 2: How can bottom-up and top-down approaches help identify opportunities for Industrial Symbiosis in the regional context?

RQ 3: What features are necessary for a top-down approach to identify industrial symbiosis opportunities at a regional level?

1.2 Scope of the research

The process of developing and implementing Industrial Symbiosis partnerships is complex and can be divided into five consecutive development stages: opportunity identification; opportunity assessment; barrier removal; commercialization and adaptive management; and documentation, review, and publication (Grant et al., 2010). The main focus of this thesis is to support the opportunity identification stage. The main objective has therefore been to develop methodologies that could help identify companies with potential to become partners in an IS, and the types and quantities of resources that could be exchanged. The methods have been limited to exchanges of material resources, and do not consider flows, such as energy or water. In addition, the research uses the Västra Götaland Region in Sweden to realize the work and provide examples of the tools and methodologies that have been developed. This thesis does not present economic assessments. The environmental assessment included in this study is limited to waste generation reduction. Finally, the scope of the thesis is the identification of IS opportunities within three main sectors, namely agriculture, mining, and manufacturing.

The thesis summarizes the research presented in the appended papers. Chapter 2 describes the theoretical background, with focus on the concept of Industrial Symbiosis. Chapter 3 explains the research design and used methods. Chapter 4 contains the results and discussion, Chapter 5 presents the main conclusions, and Chapter 6 provides insights on future work.

2 THEORETICAL BACKGROUND

2.1 Types of Industrial Symbiosis

A variety of ways in which Industrial Symbiosis partnerships can emerge have been documented, including self-organization, facilitation by organizations or individuals, and top-down planning of eco-industrial parks (Paquin and Howard-Grenville, 2012) (Figure 1). Self-organized IS occurs when two or more private partners start sharing resources, traditionally for economic reasons (Chertow and Ehrenfeld, 2012a). Top-down planning happens when deliberate actions to relocate industries to a specific place in order to facilitate resource exchanges are taken by external actors (Boons et al., 2011). This relates for instance to some of the eco-industrial parks. Partnerships formed after facilitation by organizations or individuals occur when a third party, or facilitator, which can be an institution, university or other type of organization, bring together two companies with the potential to collaborate in an IS partnership.

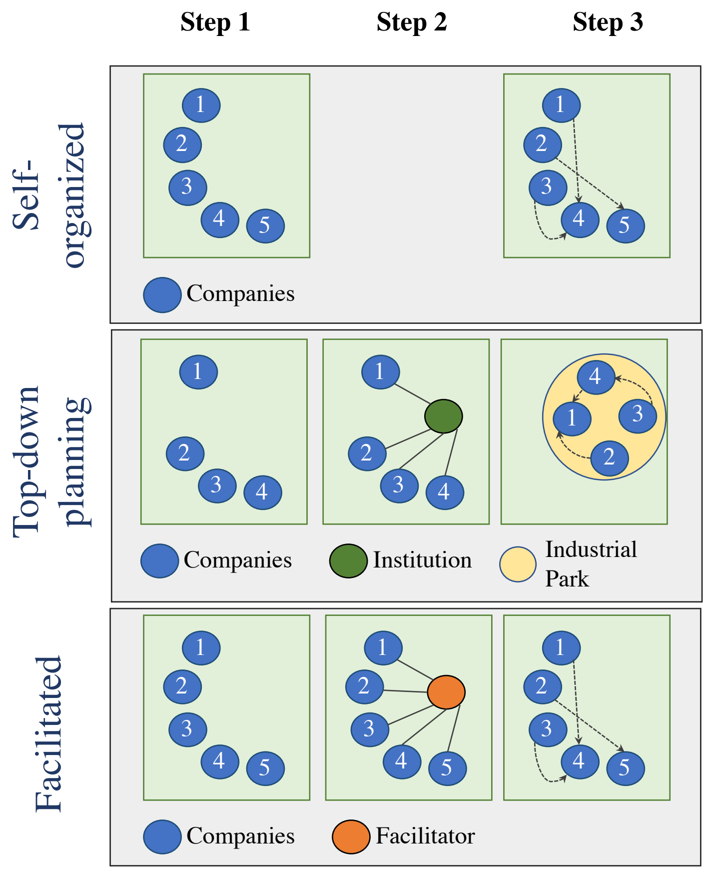


Figure 1 – Types of Industrial Symbiosis (adapted from: Grant et al., 2010)

There are several examples of successful implementation or development of eco-industrial parks, the best known being Kalundborg. Another example can be found in South Korea, as part of a national 15-year program, which started in 2005. In the first 5 years, 47 IS partnerships were developed and implemented at five eco-industrial parks (Park et al., 2016). On the other hand, according to Sakr et al. (2011), a significant number of eco-industrial park projects have failed. There are documented reasons that explain why some of the planned eco-industrial parks were not successful. One of the reasons for the failure was that the companies involved in the projects considered the potential exchange relationships financially risky. A second reason was the lack of trust towards the entity responsible for the project. Finally, in some cases there was an obligation for companies to relocate to another site, closer to the by-products, a requirement that a number of companies were not willing to accept (Sakr et al., 2011).

Facilitated IS projects, initiated by the companies themselves, but with financial and/or advisory support from an external facilitator, such as a local or regional authority, or university faculty, were more successful (Paquin and Howard-Grenville, 2012; Posch et al., 2011; Sakr et al., 2011). Generally, the role of the facilitator is to bring together companies that lack information, experience, knowledge, or contacts with other interested companies (Paquin and Howard-Grenville, 2009). A facilitator can for instance perform a simple optimization exercise by holding a meeting to bring companies together or copying a successful case study of input-output matching reported in the literature.

2.2 Industrial Symbiosis in the regional context

Several studies and programs aiming to facilitate, initiate, and foster IS at the regional revel have been carried out. One of the best-known programs is the National Industrial Symbiosis Program (NISP). NISP started in 2003, as a pilot study of three regions in the United Kingdom, supported by regional development agencies and the hypothecated landfill tax fund (NISP, 2017). The success of the program lead to expansion to the national level, which began in 2005. Nowadays the program is divided into 12 practitioner teams across regions in UK. Due to its success, NISP has now been replicated at regional and multi-regional level in 30 countries across five continents.

Implementation of IS at the regional scale provides several benefits. First, by considering a larger area, more heterogeneous wastes are generally available, as well as a greater number of potential customers that may be able to use the available resources. According to Jensen (2016), diversity within industrial ecosystems promotes resource reuse and, potentially, increased system production. Secondly, a region may provide the necessary volumes to achieve the economies of scale required to ensure the profitability of an IS partnership (Cutaia et al., 2015; Posch, 2004; Sterr and Ott, 2004). Finally, the regional scale ensures proximity between the companies. Although geographical proximity is not a requirement for IS partnerships to work (Lombardi and Laybourn, 2012), it is still an important factor in the formation of partnerships (Chertow and Ehrenfeld, 2012b).

One characteristic that may be important for IS creation is the typology of companies in terms of company size within a region. In the European Union, micro, small and medium-sized enterprises (SMEs) represent more than 99% of the total number of companies, the majority of which have fewer than ten employees (Eurostat, 2015). As they represent the majority of enterprises, SMEs have become increasingly important in our society, providing employment opportunities as well as economic growth, and acting as key players for local and regional well-being (European Commission, 2008). However, compared to larger companies, SMEs face many challenges. For instance, improving the environmental performance is often much harder for SMEs due to a lack of information, insufficient expertise, or human and financial resource scarcity (European Commission 2008). A possible way to increase the sustainability of SMEs is to consider the potential of utilizing IS in their activities, however for this to be possible, there is a clear need for support from different institutions in the development of such strategies.

Despite the fact that the number of larger companies in a region is much smaller, they may play an important role in IS partnerships. As a rule, these industries are important catalyzers for symbiotic connections in a region (Patrício et al., 2015). This is because they traditionally generate, or need, larger quantities of by-products that can be utilized in IS partnerships (Chertow, 2000). They have been defined in the literature as ”physical anchors” (Chertow, 2000). Additionally, large companies can provide examples of good practice, thereby encouraging other companies in the same region to look for similar partnership opportunities.

To enable the transformation of environmental challenges into business opportunities, it is clearly beneficial to consider all the entities operating in a region. By considering a larger sample of companies, both SMEs and larger enterprises, the probability of finding opportunities for IS partnerships will also increase. In this context, facilitated IS may play an important role and help establish links between companies operating in a region. Connections could be made by taking on environmental challenges together as partners, and by identifying new opportunities to increase efficiency, competitiveness, and innovation (European Commission 2008). Studies have shown that companies engaging in IS often do so because of third-party stakeholders (e.g. regional developers, local authorities or industrial associations) with an interest in promoting the development of this type of activities (Ormazabal et al., 2018; Paquin and Howard-Grenville, 2012; Park et al., 2018). This indicates that third-party stakeholders can play a very important role in facilitating the process of IS development. Regional developers, local authorities, and industrial associations are examples of facilitators that can overcome some of the problems preventing companies from implementing Circular Economy practices, including short-term vision and lack of time (Granello and Wheaton, 2004). This shows that companies need support from public institutions when trying to implement Circular Economy strategies. Additionally, institutions such as industry associations may play an important role by putting in place measures aimed at encouraging their affiliated members to enter into IS partnerships (Biondi et al., 2002; Ormazabal et al., 2018). Industry associations may enable companies to improve their business performance by fostering information sharing, offer training, or build cooperatives (Aldrich and Staber, 1988). However for this to be possible, facilitators themselves need tools and methods that help them to identify potential IS partnerships.

2.3 Identification of opportunities for Industrial Symbiosis

There are a number of methods that can be used to identify potential IS partnerships, including New Process Discovery, Relationship Mimicking, Material Budgeting, and Input-Output Matching (Grant et al., 2010; Holgado et al., 2018). These tools can be used individually or in combination (Holgado et al., 2018). New Process Discovery occurs when a novel approach to transforming a by-product into a valuable resource is found. Relationship Mimicking involves finding successful IS case studies, then applying the same concept to similar organizations (Grant et al., 2010). Material Budgeting involves identifying flows of materials, energy and water within a system, using tools such as Material Flow Accounting (Chertow, 2000). Input-Output Matching is perhaps the most commonly used method. It involves finding links between the outputs and inputs of different companies and is normally performed using workshops or online platforms (Grant et al., 2010). It can for instance be used to achieve higher efficiency in industrial parks (Holgado et al., 2018), via IT-enabled identification using semantic matching (Trokanas et al., 2014) or expert-facilitated workshops (Maqbool et al., 2019). The most widely known tool within Input-Output Matching is the National Industrial Symbiosis Program (NISP). NISP uses a bottom-up, facilitated method to encourage IS in a given region. To find symbiosis opportunities, workshops rather than technical studies are used. By using a cross-sector and supply chain approach, NISP is able to identify opportunities among stakeholders participating in the workshops (NISP Canada, 2017).

French Presteo, a Swiss symbiosis identification methodology, and E-Symbiosis are other examples of Input-Output Matching tools (Maqbool et al., 2019). The majority of these tools require extensive commitment from companies in order to produce results (Cutaia et al., 2015). One example is the E-Symbiosis tool, which was a web-based platform enabling users to initiate IS partnerships (E-symbiosis, 2017). Companies were asked to register the resources/wastes they wanted to share, including quantities and units of measure. They were also able to define the resources they required as inputs. The matching was performed automatically by the platform, which suggested potential partnerships. Once the IS opportunities had been identified, companies were able to engage with each other to discuss the proposed synergy. The project was co-founded by the European Commission and originally implemented in Greece and the United Kingdom. This saved 4.4 million tons of carbon and prevented 3.39 million tons of waste from ending up in landfill (E-Symbiosis, 2017). Nevertheless, neither French Presteo nor the E-Symbiosis tool are operational anymore (Maqbool et al., 2019).

The previous examples show that efforts have been made to encourage IS at the regional level. The majority of the existing tools and programs are based on bottom-up approach, requiring companies to perform certain activities, such as registering resources/wastes on web platforms, or sharing information by participating in workshops or meetings (Alvarez and Ruiz-Puente, 2017). However, some constraints can limit the necessary data acquisition indispensable to identify potential IS opportunities, including: 1) Data confidentiality. There are multiples examples of companies not willing to share confidential information, e.g., raw material consumption or waste production (Bacudio et al., 2016). Companies also hesitate to share information if they do not see clear value gain (Patala et al., 2020); 2) Time constraints, and high costs. When considering an entire region, conducting audits and interviews to collect information about inputs and outputs is associated with high costs and may be very time consuming (Hein et al., 2016), and; 3) Other reasons. There might be the case that companies simply were not considered for a workshop, did not register their wastes on an online platform, or did not fill in a questionnaire.

A more systematic approach to identification of IS opportunities would enable all companies operating within a given region to be considered, without any need for direct contacts with the companies. However, establishing an IS partnership, i.e. finding a partner firm for material exchange, requires detailed data at company level (Chen and Ma, 2015). This means that identification of the inputs and outputs at company-level is fundamental to finding new potential IS partnerships (Song et al., 2017). Yet, gathering comprehensive and standard databases for materials has proven to be difficult Chen and Ma (2015). This is even more evident for waste generation datasets, that usually are just available with very high aggregation (Reynolds et al., 2016).

This thesis tries to close the identified gaps, by developing top-down methods to identify opportunities for industrial symbiosis partnerships, without the need of a first contact with companies. This becomes even more important when regional scale is taken in consideration, due to the large number of companies that can be found. Using available statistical data, and comprehensive datasets, the thesis aims as well to develop methods that allow for identification of potential relations between multiple sectors. As stated before, considering different industries at the same time widens the possibility to find potential applications for waste reuse in a particular geographical area, taking advantage of the diversity within industrial ecosystems to promote resource reuse across industry sectors.

3 METHOD

3.1 Research design

The method for the research presented in this thesis is illustrated in Figure 2. The method is divided into 3 parts: a pre-study; the methodology development; and the methodology application and prioritization. Chapters 3.3-3.5 present summary of each part that are described in full in the appended papers (see Figure 2 for reference to corresponding papers).

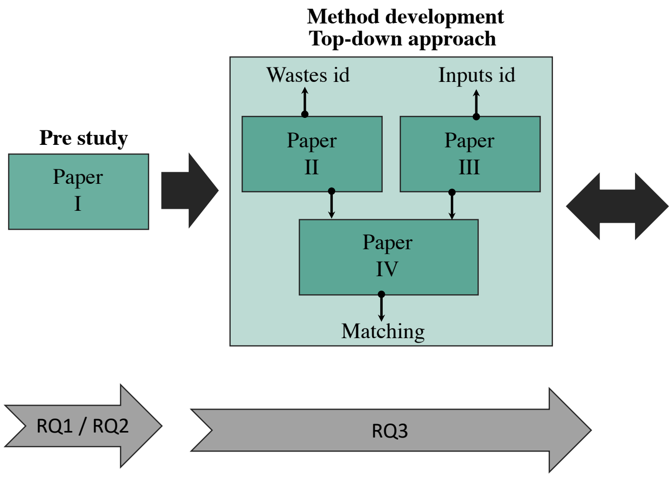


Figure 2 *- Research Design/Method*

<u>**The Pre-study part**</u> was designed to answer RQ 1 and RQ2:

RQ 1: Which challenges do companies face to become a partner of an Industrial Symbiosis?

RQ 2: How can bottom-up and top-down approaches help identify opportunities for Industrial Symbiosis in the regional context?

First, this part of the study contributes to understanding which information and methods are needed to identify an industrial symbiosis opportunity. Then, challenges in identification and realization of IS partnerships are studied in order to identify research and development gaps that can be addressed with this research thesis. The used research methods were a literature review and an empirical study.

The empirical study investigated the main challenges that Small and Medium Enterprises face to become a part of IS partnerships. To examine this, interviews were performed with companies within two different industries in the Västra Götaland Region in Sweden. The Pre-study also examines the main advantages and challenges of applying both bottom-up and top-down approaches at a regional level. This is performed by testing bottom-up and top-down approaches to identify and propose potential IS partnerships in the Västra Götaland Region. The Pre-study is described in detail in Paper I.

The **Methodology Development** part of the method consisted of developing a methodology to identify industrial symbiosis partnerships at a regional level using a top-down approach. The core idea was to develop a systematic and comprehensive method that enables identification of partnerships in three steps: 1) identify wastes generated by industries, 2) identify material inputs needed by industries, and 3) link relevant wastes to materials inputs in order to identify potential industrial symbiosis partnerships.

The Research Question 3 was therefore divided into 3 Sub-Questions, which were addressed in Paper II, III and IV respectively. The RQ 3 and the Sub-Questions were:

RQ 3: What features are necessary for a top-down approach to identify industrial symbiosis opportunities at a regional level?

RQ 3.1: Is it possible to map the types of wastes that industries usually generate using a systematic top-down approach?

A method that identifies the wastes potentially produced by different industries was developed. The method employs routinely reported statistical data for industries, which enables simple data acquisition and ensures any changes in the production processes and waste generation are captured. See Section 3.4.1. and Paper II for the details of developing this part of the methodology.

RQ 3.2: Is it possible to map the types of material inputs needed by industries using a systematic top-down approach?

A top-down method for identifying material inputs to industries at product level was developed. The method employs routinely reported statistical data for industries, namely International Trade data, which enables simple data acquisition and ensures changes in the production processes are captured. See Section 3.4.2. and Paper III for the details of developing this part of the methodology.

RQ 3.3: Is it possible to map potential Industrial Symbiosis opportunities by matching generated waste and material inputs?

A top-down method was developed to identify opportunities for Industrial Symbiosis partnerships. This was achieved by using IS case studies found in the literature, identifying industries that produce the same types of wastes (Donors), and industries with the potential to receive certain types of waste as material input (Receivers). A matchmaking process was then applied, linking multiple waste donors and receivers. See Section 3.4.3. and Paper IV for the details of developing this part of the methodology.

The Methodology Application part aims to apply the method to different case studies and to identify potential improvements or additional features that a top-down method should have.

The developed top-down methodology was applied to identify opportunities for IS partnerships in three case studies: one for wood wastes (see Section 3.5.1 and Paper IV), one for biogas (see

Section 3.5.2 and Paper III), and another for Carbon Capture and Utilization development (see Section 3.5.3 and Paper V). A need to prioritize obtained IS partnerships was identified at the methodology application step. Prioritization was developed by applying selection criteria relevant for the case study. For wood waste case study (Paper IV), geographical proximity is used as the main criterion in the prioritization of potential IS partnerships. Within the biogas study (Paper III), methane yield is the criterion, as this parameter enables selection of wastes with higher potential for biogas production. Lastly, in the Carbon Utilization study (Paper IV), the selection criteria were CO_2 purity for the CO_2 sources, and the technical requirements of CO_2 utilization technologies.

The developed methods were tested in Västra Götaland, a coastal region in western Sweden. According to the Swedish Statistical office (SCB), the region had a population of approximately 1,691,000 in 2018, which represents 17% of Sweden's population. In total, the Västra Götaland Region has 49 municipalities. The region hosts a wide range of industries from different sectors, including trading, shipping, agriculture, forestry and manufacturing industries (Lansstyrelsen, 2015). The Västra Götaland region includes the second largest metropolitan area in Sweden, the Gothenburg Metropolitan Area. Gothenburg M. A. encompasses 13 municipalities and has a population of 0.95 million. In 2008, the service sector was responsible for 77% of the employment, while the industrial and construction sectors employed 16% and 7% of the workforce, respectively. The largest port of Scandinavia is situated in Gothenburg. Almost 30 % of the Swedish foreign trade passes through this port (Port of Gothenburg, 2015).

In order to answer the aim of the study, this thesis combines a set of approaches and methods. Both, Qualitative and Quantitative research approaches were used. Qualitative research deals with words and meanings. The main Qualitative research method used in the Thesis was semi-structured interviews applied in the first part of this thesis, Pre-study (Paper I in Section 3.3). Flexible interviews were used, in which the order of the questions may change, and new questions may come up, to follow-up on answers given by the interviewee (Bryman and Bell, 2015). The interviews allowed on a better understanding and analysis of the main challenges that companies face to identify partners to cooperate in industrial symbiosis partnerships. Quantitative research deals with number and statistics. The main Quantitative research method used was Material Flow Accounting (MFA), a key tool in industrial ecology. MFA is based on the law of conservation of mass and has been defined as ‘a systematic assessment of the flows and stocks of materials within a system defined in space and time’ (Brunner and Rechberger, 2003). In this study, MFA fundamentals were used to identify wastes and material inputs generated or used by industries, presented in section 3.4.1 and 3.4.2 respectively.

Other important methods used in this thesis include Input-Output Matching and Geographic Information Systems (GIS). Input-Output Matching consists of finding possible Industrial Symbiosis matches by analyzing characteristics of the output’s streams (i.e. wastes and by-products), the characteristics of industries material inputs, and finally matching one to the other (Bin et al., 2015; Hein et al., 2016; Low et al., 2018; Yeo et al., 2019). This approach relies on the technical information about stream characteristics and technological capabilities rather than on the willingness and knowledge of the companies to share the data (Yeo et al., 2019). Input-

Output Matching was the core method used in Section 3.4.3 to identify potential links between wastes and materials inputs. Finally GIS mapping, consists of managing, storing, analyzing, and visually presenting geographical information. In this thesis, GIS is used to put the obtained results in map format for visualization and additional analysis, see Section 3.5.

3.2 Data sources

3.2.1 Datasets

Statistical databases are at the core of top-down method development. Table 1 presents the main databases used in this study. The table shows the name of each database, its source, a short description, and the temporal and spatial resolution. The majority of the data was acquired from official publications and databases from a large array of organizations and institutes. However, in some particular cases, the databases had to be acquired under a special agreement due to confidentiality restrictions.

Table 1 *- Main datasets used in the thesis*

Database	Source	Description	Paper I	Paper II	Paper III	Paper IV	Paper V	Temporal and Spatial Resolution
International Trade Statistics (ITS)	Statistics Sweden (SCB)	All products (8-digit CN codes) imported/exported in a specific year at country level. For each transacted product there is information on the industry (NACE code) that imported the product, as well as the quantity (in tons), and economic value (SEK).			■			Annual International Trade data for 13 years (2000 to 2012) imported and exported to and from Sweden.
International Trade Statistics (ITS)	Instituto Nacional de Estatistica (INE)	All products (8-digit CN codes) imported/exported in a specific year at country level. For each transacted product there is information on the industry (NACE code) that imported the product, as well as the quantity (in tons), and economic value (Euro).			■			Annual International Trade data for 13 years (2000 to 2012) imported and exported to and from Portugal.
Industrial wastes	Eurostat	Industrial waste generated within each sector		■				Data at sector level and per waste type (EWC 42), for countries in Europe. Data for 2014
Industrial wastes	INE Portugal	Detailed data on wastes generated (LoW) by industry		■			■	Data at NACE 4-digit level, for Portugal, for 5 years (2000 to 2012)
Number of employees	Eurostat	Number of employees per sector		■			■	Data for all NUT III regions and countries in Europe. Data for 2014
Locations of industries	SCB	Spatial location of companies, their size (no of employees), and NACE code (5 digits)	■	■		■		Data for companies with 3 or more employees operating in Västra Götaland. Data for 2013
Industrial production	Eurostat	Industrial production by product type (in units and economic value)					■	Data at country level (EU28) and product level (Prodcom), for 2012
Emissions of Carbon Dioxide	Regional Development and Cooperation (RUS); Statistics Sweden; Swedish EPA	CO_2 emissions, both from fossil fuels and biomass origin.					■	Data at Facility level (companies that emit more than 100.000 kg CO2 / year). Data for 2012

3.2.2 Nomenclatures

In this thesis, industries, material inputs and wastes are classified according to Eurostat's (statistical agency of the European Union) standard nomenclatures. Each of the used nomenclatures is explained in more detail below. Correspondence tables relating EU nomenclatures to other worldwide nomenclatures are available (Ramon, 2020).

Statistical classification of economic activities

Industries are classified using the Statistical Classification of Economic Activities in the European Community nomenclature (NACE). Revision 2 was mostly used, and covers a total of 615 4-digit NACE codes. As an example, industry 1711 refers to manufacturing mechanical or semi-chemical pulp companies. Activities can be further aggregated into 3-digit NACE codes, which includes a total of 103 industries. Following the same example, companies manufacturing mechanical or semi-chemical pulp are included in NACE 171, Manufacture of pulp, paper and paperboard.

Industries can also be aggregated into NACE sections (21 in total). Because the manufacturing section is too large, it has been further disaggregated into 10 subsections based on Eurostat praxis. This disaggregation is a common practice in Eurostat's methodologies for waste reporting, which are defined in regulation (EC) No 2150/2002 of the European Parliament and of the council on waste statistics (Eurostat, 2008). The sections and subsections considered in this study are defined as sectors (see Supplementary Information Table 3 in Paper II). As an example, industry 1711 is included in the manufacture subsection C17-C18 (manufacture of paper and paper products sector).

Combined Nomenclature

Combined Nomenclature (CN) is the nomenclature used in this study to classify material inputs. The CN integrates the Harmonized System, an international multipurpose nomenclature for classification of traded products. The CN consists of approximately 10,000 8-digit codes, each assigned to a different product. The codes can be aggregated into hierarchical subcategories, specified by the number of digits. For example, each 4-digit CN code is a subcategory heading and consists of approximately 1,250 groups of products. The 4-digit CN codes have been used in this study because at this level of detail, there are few differences between years, which makes it possible to aggregate and/or compare data for multiple years. As an example, CN code 4407 stands for "wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness of > 6 mm". The complete list of 4-digit CN codes can be found in Supplementary Information, Table 2 in Paper III. In this study, 4-digit codes are referred to as 'material inputs'.

European Waste Catalogue and List of Wastes

The industrial wastes are classified according to the European Waste Classification for Statistics (EWC-stat) and List of Wastes (LoW) nomenclatures, also developed by the European Union. EWC-stat, covers 12 waste groups (hereinafter EWC12), and further subcategories. The secondary category includes 42 waste groups (hereinafter EWC42, see supplementary information Table 1 and 2 for a complete EWC-stat list). The LoW nomenclature encompasses 839 wastes types, each assigned to an EWC12 and an EWC42 category. As an example, LoW code 30101 stands for "waste bark and cork", and belongs to the EWC12 category "07 Non-metallic wastes" and the EWC42 category "07.5 Wood wastes".

3.3 Pre-study (Paper I)

The research conducted in Paper I tested both bottom-up and top-down approaches. The bottom-up approach involved semi-structured interviews with 18 companies from 2 industries; mushrooms producers and breweries. The purpose of the interviews was to identify the wastes generated by individual companies, and to verify whether the companies already shared their wastes within an IS partnership. The interviews also aimed to assess barriers, and current and future motivations for companies to share wastes with other stakeholders in IS partnerships. Qualitative research, including topics coding, was performed to analyze all the collected data. This encompassed classifying and labelling the information gathered in the interviews into topic codes, which can be found in Table 1 in paper I.

The top-down approach comprised the identification of potential opportunities for IS collaborations. The Relationship Mimicking method was used to identify new potential opportunities for IS partnerships (Grant et al., 2010). This involved finding successful IS case studies, both in the literature and as identified during the bottom-up step. Finally, opportunities for IS partnerships were mapped considering: Waste Donors, i.e. companies working in the same industry as the ones that were interviewed; and Waste Receivers, i.e. companies identified as having the potential to use the wastes as inputs (see Table 4 in Paper I for descriptions of opportunities). All the companies mapped were active within the Västra Götaland region, according to their 4-digit NACE code, and company directories available online (e.g.: Allabolag). The mapping was performed using Geographic Information Systems (GIS).

3.4 Top-down methodology

The core work performed in this thesis was the development of a top-down methodology to identify potential opportunities for IS partnerships. An illustration of the developed methodology is presented in Figure 3. The approach was developed in four main steps. The first step involved identification of amounts and types of wastes expected to be generated by industries. The second step was to develop industry-specific material input databases, describing generic material inputs used by industries. These two steps were conducted systematically in order to consider all industries. Step three involved matching the wastes with the material inputs to identify potential opportunities for IS partnerships. The fourth and final step was to select criteria used to prioritize IS partnership opportunities and mapping the obtained opportunities. This last step is exemplified in different case studies. All the steps are described in detail in the following sub-sections.

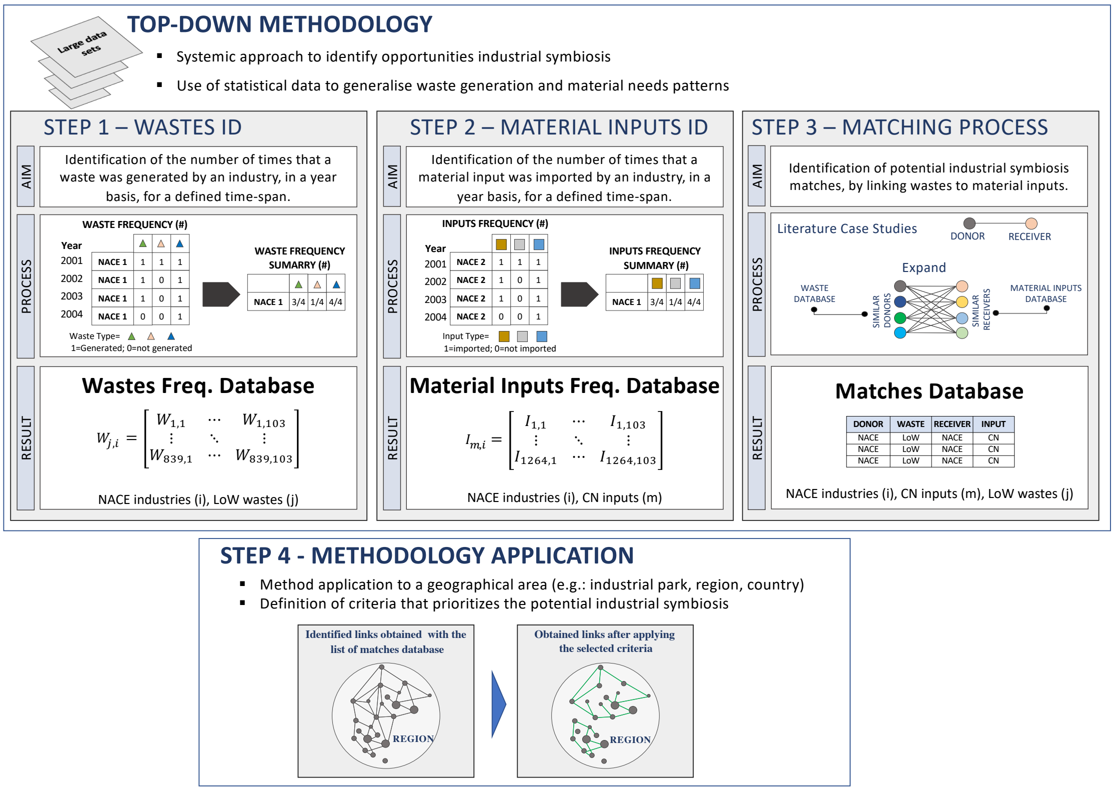


Figure 3 - Illustration of the developed top-down methodology (adapted from Paper V)

3.4.1 Identifying generic wastes (Paper II)

In Paper II, a systematic method for identification and quantification of the wastes generated by different industries was developed. The method was divided into four steps: Waste generation intensity; Waste characterization by sector; Detailed waste characterization by industry; and Waste frequencies by industry. Each step is described in the following paragraphs.

The Waste generation intensity step quantified the amounts of wastes generated by industries in a given sector. The waste generation was allocated based on the assumption that it is correlated to the number of employees working in each industry (Naturvårdsverket, 2014; Salhofer, 2000). Consequently, the Waste Factor per employee (WF) reflects the total waste generated by a given sector within a country, in relation to the number of employees in that sector. Estimates were performed using national data, available in Eurostat for 28 European countries. Analysis of Variance (ANOVA) was used to evaluate the statistical significance between waste generation and number of employees, with the null hypothesis that this is false and the alternative hypothesis that the relationship exists. Subsequently, a regression line was fitted to the available data points, and the respective coefficient of determination (r^2) was calculated. A log-log regression model was used.

Step two encompassed the waste characterization by sector. This involved the development of waste generation profiles for 12 sectors and the proportions of EWC-stat wastes they generate, defined as Sector Waste Ratio (SWR). The Sector Waste Ratio was calculated as the share of waste j in relation to the total amount of waste from sector k in country z (Equation 1). The SWR was calculated for 28 European countries and for each of the EWC 12 and EWC 42 waste categories. Median and mean values, as well as higher and lower quartiles were calculated. Outliers were defined as values that were 1.5 times higher or lower than the upper or lower quartile.

$$SWR_{jkz} = \frac{W_{jkz}}{\sum_{j=1}^{12} W_{jkz}} \qquad \textit{Equation 1}$$

SWR - Sector Waste Ratio in tons/tons
W – Amount of waste produced, in tons
j – Waste type, in this case primary category of EWC, which includes 12 groups of waste (EWC12)
k –Sector
z – Country

Detailed waste characterization by industry involved the development of waste generation profile databases for industries. Data included the proportion of wastes (by EWC42 category and LoW) generated by individual industries. The amount of each EWC42 and LoW waste type generated by each industry was divided by the total amount of waste produced within the same industry (Equation 2), here defined as Industry Waste Ratio (IWR).

$$\overline{IWR}_{ji} = \frac{1}{t}\sum_{t=1}^{4} \frac{W_{jit}}{\sum_{j=1}^{42} W_{jit}} \qquad \textit{Equation 2}$$

IWR - Industry Waste Ratio in tons/tons
W – Amount of waste produced, in tons
i – Industry
j – Waste type, in this case secondary category of EWC, which includes 42 groups of waste (EWC42)
t – Available years

The aim of Step four was to set up a database with the generation frequencies for different waste types (LoW) per industry. The result, the Waste Frequency database, presents the annual frequency for each waste type generated by each industry, during a pre-defined time span (Equation 3). As previously explained, each industry consists of a set of companies operating in the same field. The frequency value is the number of years in which at least one company within a particular industry generated a specific waste type within a set time span. This means that if only one company in a particular industry generated a specific waste type in a given year, the frequency value is 1, regardless of the amount of waste generated. The time span used in this study was 4 years, and the frequency values can therefore vary from 0 to 4. As an example, a frequency value of 2 means that at least one company within a particular industry generated a specified waste in 2 of the 4 years. This does not necessarily have to be the same company. Following the same example, a frequency value of 2 can also mean that 2 companies within the same industry each generated the same waste type once in 2 different years. A frequency value of 4 represents a waste that is highly likely to be generated by a certain industry, and 0 represents a waste that is unlikely to be generated within a given industry.

$$\mathrm{W}_{j,i} = \begin{bmatrix} W_{1,1} & \cdots & W_{1,103} \\ \vdots & \ddots & \vdots \\ W_{839,1} & \cdots & W_{839,103} \end{bmatrix} \qquad \textit{Equation 3}$$

W = Waste Frequency database
j – Waste type, in this case secondary category of LoW, which includes 839 types of waste
i – Industry (NACE)

3.4.2 Identifying generic material inputs (Paper III)

Paper III developed a method for identifying generic input materials used by industries. The method resulted in two databases: a Material Input Frequency database and a Weight Fraction database. The Material Input Frequency database provides the annual frequency of material inputs used by individual industries over a period of time (Equation 4). It is the equivalent of the Waste Frequency database (see Section 3.4.1), but for material inputs. For instance, if only one company within a particular industry needs to import a certain material in a given year, the frequency value assumes the value 1, regardless of the imported quantity. The Material Input Frequency database was populated using annual data for 13 years. The value 0 corresponds to a material that was never used, and the value 13 relates to a material that was used in all the years.

$$\mathrm{I}_{m,i} = \begin{bmatrix} I_{1,1} & \cdots & I_{1,103} \\ \vdots & \ddots & \vdots \\ I_{1264,1} & \cdots & I_{1264,,103} \end{bmatrix} \qquad \textit{Equation 4}$$

I = Material Input Frequency database
m– Material type (CN) which includes 1264 types of materials
i – Industry (NACE)

The validation process analyzed the differences between the obtained frequencies for each product, and for each industry, in the Material Input Frequency databases obtained from different datasets (e.g. geographically and import or export). The Frequency Value for each transaction in one database was subtracted from the result for the corresponding transaction in another database. When the obtained differences were zero or very small, the frequency results were considered to be verified.

The Weight Fraction database shows the proportion of each material input in relation to all the other materials needed by a specific industry. In this case, the mass (in tons) of imported products was divided by the total mass (in tons) imported by the industry. The calculations were performed for each available year, and an average value for the time span was obtained. To analyze similarities between proportions of material inputs for each industry, the validation process included a comparison of similarities for each vector of each industry, in terms of percentage of material inputs needed. The cosine similarity method was chosen to evaluate the similarities between industry input vectors obtained for Swedish and Portuguese imports, respectively.

3.4.3 Matching wastes with material inputs (Paper V)

Paper V aimed to identify potential IS partnerships by matching companies using the records in the Waste Frequency and Material Input Frequency databases described in Section 3.4.1 and 3.4.2, respectively. The main concept behind the matching process was to use successful IS case studies and search the frequency databases for other industries that generate similar wastes (Donors) and need similar material inputs (Receivers). With this approach, it was possible to expand each case study partnership into multiple potential relations. To test the approach, the study used the MAESTRI database, which contains IS case studies, collected as part of an EU-funded research project (MAESTRI project, 2020).

The matchmaking process was performed using an iterative process. For each IS case study in the MAESTRI database, a link between generated waste and the material input that this particular waste could replace was made. Then, all industries that generate similar types of waste (i.e. potential Donors), were identified using the Waste Frequency Database (Section 3.4.1). All industries that may be able to use this waste as material input (i.e. potential Receivers) were identified, using the Material Inputs database (Section 3.4.2). Based on this information, all potential donors were linked to all potential receivers, creating a large set of potential IS matches. This procedure was applied to all IS links in the MAESTRI database. All the obtained matches were collected in a Matches database. Each row in this database contained four fields: 1) the Donor industry, represented by a NACE code; 2) waste that this industry may generate, represented by the LoW code and the corresponding Waste Frequency; 3) the material input that this waste could replace, represented by the CN code, and the corresponding Material Input Frequency, and; 4) the Receiver industry that may be able to use the waste, represented by its NACE code.

The method was applied spatially by mapping opportunities for IS partnerships between industries in a defined geographical area. A database containing the locations of the companies and their respective NACE codes was used. This database was then linked to the Matches database, to identify potential IS partnerships (see Section 3.5 for method application to case studies). The final output of the method was a list of links with between companies with the potential to form IS partnerships. The list also contained information on the type of waste that could potentially be exchanged, and the potential material input. Additionally, the available Waste and Material Input frequencies can be used as the initial criterion for prioritizing the obtained links.

3.5 Top-down methodology application

Three case studies were set up to apply the top-down method developed in Section 3.4: one for wood wastes (Paper IV), one for biogas (Paper III), and another for Carbon Capture and Utilization development (Paper V). Additionally, the developed top-down methodology was complemented with criteria designed to aid the selection of symbiosis opportunities with higher potential.

3.5.1 Wood waste application (Paper V)

In this case study, all companies that generate sawdust (LoW 30105) and companies that may use it as a raw material were linked as potential IS partners. This was done by applying the Matches database developed in Section 3.4.3 to the database of companies operating in the Västra Götaland Region, containing information on their geographical location, NACE code, and company size (number of employees) for each company with more than two employees. In this way, all companies within the region that may generate sawdust, as well as the ones that may use it as raw material were identified. In the next step, the stronger potential symbiosis opportunities were identified using three criteria: distance, Waste Frequency and Material Input Frequency. Potential IS partnerships between companies located more than 48 km from each other were excluded. This distance corresponds to the upper quartile obtained from (Jensen et al., 2011), where typical resource movement distances for different waste types were calculated based on actual IS partnerships in the UK. Only companies with a Waste Frequency higher than 2, out of the possible 4, were considered, as these can be expected to generate sawdust on a regular basis. Companies with a Material Input Frequency higher than 9, of 14, were considered. Although companies with different frequency values may have the potential to be part of an IS partnership, they were considered less likely to use the waste. The obtained links between companies were mapped using GIS software.

3.5.2 Biogas application (Paper III)

The aim of this case study was to identify companies that could be included in IS partnerships for biogas production. To achieve this, the top-down methodology was complemented with two criteria. Wastes with high theoretical methane yield potential were assumed to be more suitable for biogas production, and therefore ought to be prioritized. For this reason, the primary criterion was set to the methane yield potential of each waste type. Based on available methane yield values (Murovec et al., 2015), a list of representative methane yield values (MY) for each of the EWC42 categories was created, which also included the corresponding volatile solids and total solids values (Table 1 in Paper III). Connecting the methane yield potential of each waste with the proportion of each waste types within each industry, allowed the calculation of the Industry Methane Yield potential (IMY). The Industry Methane Yield potential represents the expected methane yield for each ton of waste generated by a given industry (Equation 5).

$$IMY_i = \sum_{j=1}^{42} \overline{IWR}_{ji} \times MY_j \times VS_j \qquad \textit{Equation 5}$$

IMY - Industry Methane Yield potential in mL CH4/g-WS
IWR - Industry Waste Ratio in tons/tons as calculated in Equation 2
MY – Methane Yield representative values in mL CH4 / g VS
VS – Volatile solids in g/g-WS
i – Industry
j – Waste type, in this case secondary category of EWC, which includes 42 groups of waste (EWC42)

The biogas potential is not only dependent on the types of generated waste, but also on the quantities of waste that each industry may generate. Therefore, the Overall Methane Volume (OMV) has been calculated to illustrate the total amount of methane that may be obtained from the waste generated by an industry. The OMV was calculated for each of the industries operating in the region by multiplying the correspondent obtained Industry Methane Yield (Equation 5), by the Waste Factor (Section 3.4.2) and by the industry's number of employees, as shown in Equation 6.

$$\mathrm{OMV}_i = IMY_i \times WF_k \times E_i \qquad \textit{Equation 6}$$

OMY - Overall Methane Yield potential in m^3 CH4
IMY- Industry Methane Yield potential in mL CH4/g-WS as calculated in Equation 5
WF – Waste Factor in tons/employee
E – Number of employees
i – Industry
k – Sector

The Overall Methane Yield was estimated for the region as a whole, as well as for each of the facilities/companies operating in the region, using data on the geographic coordinates, industry type (NACE code) and company size (number of employees). The locations of the companies found to generate the most suitable wastes for biogas production were mapped using GIS software. The second criterion considered the proximity of the potential Donor to a potential Receiver. In this case study, biogas plants already operating in the region were the selected Receivers (mapped using locations available from the Swedish Gas Association - 2016).

3.5.3 Carbon capture and utilization application (Paper IV)

In this case study, the aim was to develop a method for providing detailed information on companies and processes that could potentially be involved in a CCU IS partnership at the regional level. The core concepts were the same as those developed and presented in the top-down methodology (Section 3.4), namely: identification of wastes, identification of potential users, and a matching process. Additionally, a set of criteria was applied to provide an initial assessment of the technical characteristics of each identified IS opportunity. CO_2 quantities, CO_2 purity, both for off-gases and the receiving technologies, the Technology Readiness Level, potential auxiliary inputs that may facilitate the implementation of the technology in a region, and geographic proximity were the chosen criteria.

The method was divided into 3 steps. The first step was designed to identify, quantify, and characterize the CO_2 sources present in a region. The CO_2 sources were divided into two groups, according to the magnitude of their flows: (a) medium and large-scale sources, i.e. sources that emit more than 0.1MtCO_2 per year and (b) small-scale sources, i.e. sources that emit less than 0.1MtCO_2 per year. Medium and large-scale sources were identified and mapped using the E-PRTR database[1]. Small-scale sources often produce high purity CO_2 and were identified individually. The characterization of the off-gases from both small and medium-large scale sources was performed using a generic database of CO_2 sources (Table 1 in Paper IV). This database contains information on the typical composition of CO_2-containing off-gas by industry type, collected through literature review (Table 1 in Paper IV).

In the second step, a database of CO_2-receiving processes was compiled, based on an extensive literature review of relevant articles and research projects on CO_2 reuse solutions. The database contains information on NACE codes of industries likely to use a particular technology, a short description of the CO_2 conversion methods, and the Technology Readiness Level (TRL) of each industrial process. TRL is a systematic metric system used to assess the maturity level of a technology (REF). The TRL ranking varies from 1 to 9, with 9 being the most mature process. According to the European Commission’s definition, technologies with a TRL of 1-3 are below proof of concept, those with TRL 4-6 have been tested at lab and demonstration scales, and those with a TRL above 7 are close to industrial production and commercial use. However, not all the technologies were selected for further study. The technology selection was performed according to two criteria: 1) a TRL value above 4, and; 2) the quantity of CO_2 needed globally for the production of the intermediate chemical or final product (intensity). For the second criterion, industrial processes that consume small amounts of CO_2 were not considered. Although some of these technologies have a high TRL, they are considered to be low-volume

[1] E-PRTR database - The quantification of the CO_2 emissions for each region was based on the Regulation (EC) No 166/2006 of the European Parliament and of the Council, which establishes an integrated pollutant release and transfer registry at community level (the European PRTR) (European Environmental Agency, 2015)

applications, and unlikely to increase the CO_2 demand substantially in the short to medium term. Examples include compressed CO_2 used in pneumatic energy sources, or CO_2 used for food packing or in refrigeration (Hunt et al., 2010). The final database of CO_2-receiving processes contains 17 technologies (Table 2 in Paper IV). For each of these technologies, a more extensive literature review was performed in order to identify critical information that may help facilitate the industrial partnership. The resulting database includes the conversion factor, i.e. the ratio of CO_2 use per unit of product or per unit of raw material consumed, the required CO_2 purity, and details on the operating conditions of the process (temperature, pressure, presence of catalyst). The database also includes additional information on potential auxiliary inputs that may facilitate the implementation of the technology in a region. For example, if algae production technology is considered, it would be beneficial to have a wastewater treatment plant close-by so that nutrient-rich water could be used to grow the algae. Finally, the database also includes information on whether the industrial process is dependent on the presence of a specific industry or is a stand-alone process.

Mapping of the potential CO_2 users in a specific region was performed considering two different types of companies. First, companies currently operating in the region that could use CO_2 as raw material were identified. The corresponding NACE codes were then compared with the NACE codes of a developed database of CO_2-receiving processes (Table 2 in Paper IV) to identify companies that may use CO_2. In the next step, companies and technologies that were not selected in the first step but may have the potential to be implemented in the region in the medium-term, were evaluated. These included stand-alone technologies that are not dependent on the presence of a particular industry. For example, urea-boosting technology would only be applicable if there is already a urea industry operating within the region. In contrast, the production of algae using CO_2 is a technology that does not depend on the presence of a particular industry and is therefore considered a stand-alone technology.

3.6 Additional assumptions and limitations

The application of top-down methods requires a number of predefined assumptions. Some of the assumptions have already been described in the previous methodology sections. The most important assumption in this thesis is the assumption that all companies with the same NACE code use similar technologies in their industrial processes. However, some NACE codes can be considered broad, and include more than one type of industrial plant or final product; one example is NACE code 2016, which refers to all industries that produce plastics in primary forms, without specifying the type of plastic being produced.

The developed methodologies have some limitations. Uncertainty may be seen as the main method constraint. Although statistical tests were performed for the majority of the developed methods, the overall methodology uncertainty is difficult to account. Nevertheless, the results obtained with the developed methods should be regarded as a first screening to identify potential IS opportunities. These methods were developed using the available micro data, however they could be improved if access to additional micro datasets was provided. As an example, the analysis of wastes generated by different industries was based on data from a single country. If more databases were available, additional statistical analysis could be performed to identify better correlations between the industries and the types of wastes that they generate.

4 RESULTS AND DISCUSSION

4.1 Pre-study (Paper I)

The Research Question number 1 aimed to identify challenges and drivers for companies to participate in Industrial Symbiosis (IS). To achieve this, semi-structured interviews were performed with representatives from two industries in the Västra Götaland Region of Sweden. Four out of five mushroom producers (NACE code 01135) and seven out of thirteen breweries (NACE code 11050) agreed to participate in the project, resulting in a participation rate of 60%. The case study showed that the participating companies typically face the same issues when adopting IS practices. Lack of time and lack of knowledge were some of the main aspects mentioned. The results confirmed that most companies need external support to become engaged in IS partnerships. This means that symbiosis facilitators have an important role to play, both by identifying potential IS partners, and by supporting the implementation of IS partnerships. The companies that were not already involved in any IS partnerships were paying waste management companies to handle their waste. It was observed that some companies were already engaged in IS, mostly due to the clear benefits of reduced costs and the opportunity to improve their environmental performance.

Another aim of the study was to identify advantages and drawbacks of applying bottom-up and top-down approaches to identify IS opportunities in the regional context. The bottom-up approach, which used face-to-face interviews, allowed collection of large amounts of information, including on tacit knowledge related to IS. Additionally, stakeholders gave in-depth answers, which also covered unapparent waste flows. As an example, it was discovered that some companies generate used bags (25 kg polypropylene woven bags) that are shared with other companies. It was also found that participating companies with the same NACE code consume approximately the same material inputs and produce the same types of wastes. By interviewing several companies within the same industry, it was possible to obtain valuable knowledge that allowed identification of IS best practices that can be replicated. But there were also drawbacks of applying the bottom-up approach, such as the time-consuming process required to prepare and carry out the interviews. Additionally, much of the information gathered after the first interview was repeated information.

The top-down approach consisted of identifying potential IS opportunities. This included the replication of examples of IS partnerships obtained from the interviews, as well as examples identified through a literature review (Paper I Table 4). One of the examples included in the table relates to spent grain generated by breweries, which can be used as animal feed or to produce biogas. Figure 4 shows a map with potential IS partnerships for the spent grain produced by the breweries. Average distances between potential IS partners were obtained from a study performed for the National Industrial Symbiosis Program (NISP) in the UK (Jensen et al., 2011). In that study, the average distance for food waste was 28 km. Figure 4 illustrates that all the breweries have potential Receivers within the average distance (represented by orange circles).

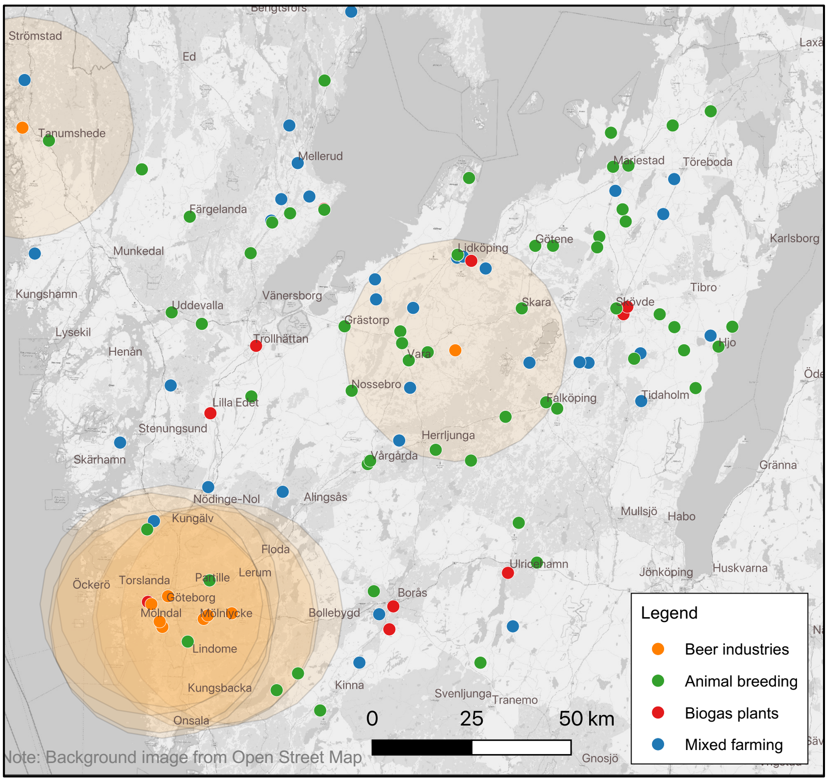


Figure 4 *– Method using top-down approach: potential Industrial Symbiosis partnerships for spent grains produced by breweries in the Västra Götaland Region (Paper I)*

The top-down approach proved to be a useful tool for identifying IS opportunities at the regional level, particularly when large number of companies were considered. The tool used the NACE code nomenclature to identify potential Donors and Receivers. The main advantage of applying the top-down method was the fast implementation, which did not require any contact with the companies beforehand, as well as the more extensive overview of the potential opportunities. However, there were also some drawbacks, including higher uncertainty than for results obtained with the bottom-up approach.

In conclusion, if a study is limited to a small number of companies, the bottom-up approach is a good choice, however this type of approach can be difficult to apply to a large number of companies. In this case, a top-down approach should be chosen. The conclusion is that if the aim is to study an entire region and analyze multiple industries at the same time, a top-down approach is the best choice. However, there are several layers of information that must be collected and analyzed, including the identification of generated wastes and required material inputs for each industry. In the next section, each step of the developed top-down methodology is presented.

4.2 Top-down methodology

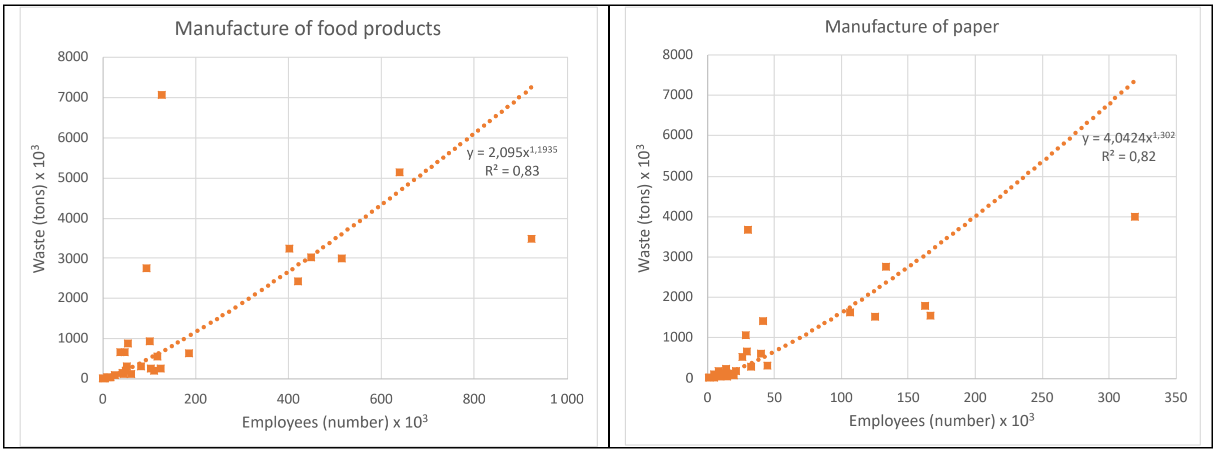
The top-down methodology is performed in three steps: Identification of generic wastes; Identification of generic material inputs; and Matching of wastes to material inputs. A summary of the results obtained in each step is presented in the following sections.

4.2.1 Identification of generic wastes (Paper II)

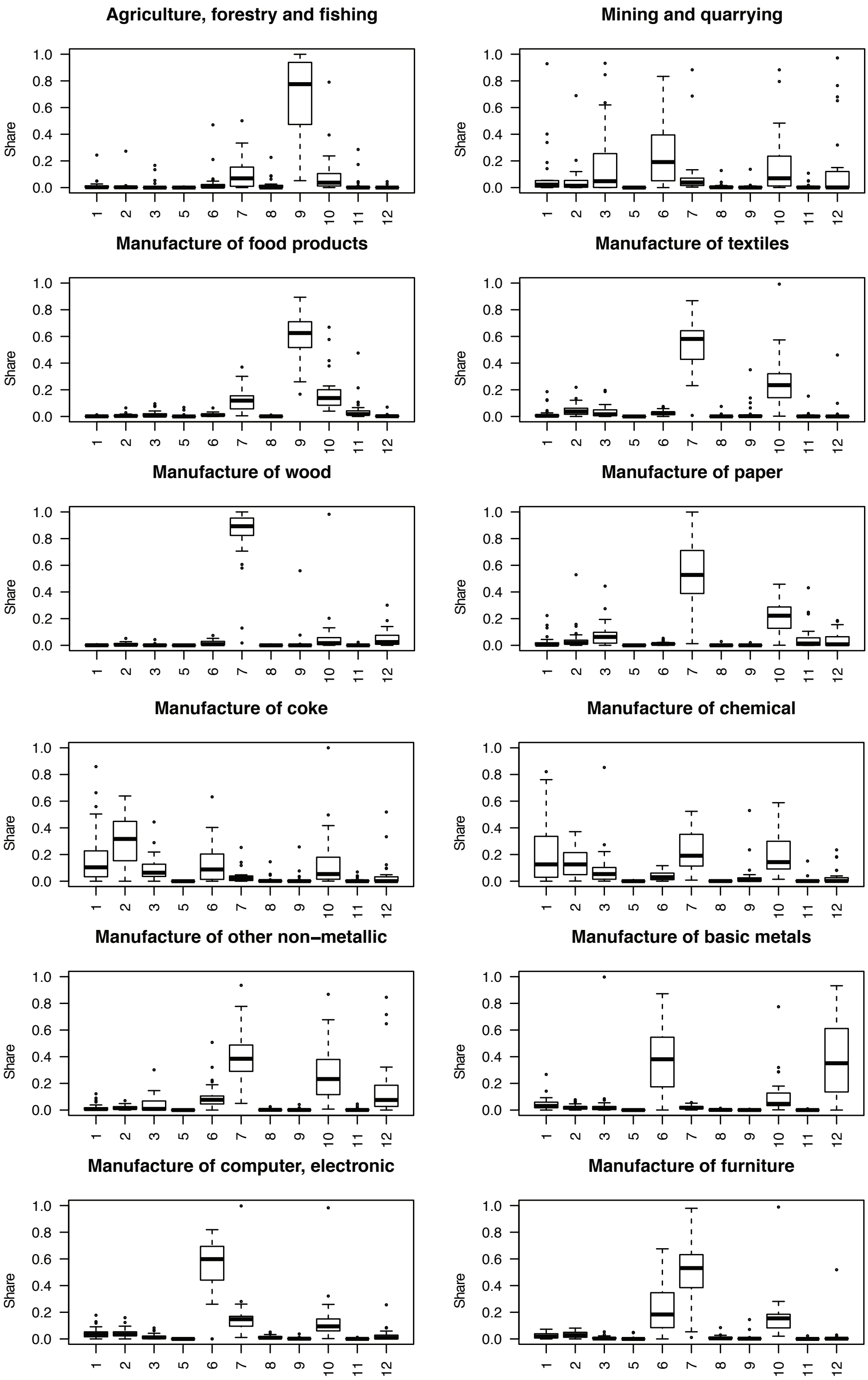
Research Question number 3.1 aimed to verify whether it is possible to identify wastes commonly generated by industries using a top-down approach. Quantification of the total amount of wastes generated by a sector was related to the number of people it employs, using the Sector Waste Factor, WF. Figure 5 shows some examples of the expected total waste generated per employee, by sector, based on data for 28 EU countries. The results of ANOVA tests showed that the relationship between the number of employees and the amount of waste generated was statistically significant in every industry sector (as the p values for all relations were lower than 0.001). This means that the amount of generated waste increases as the number of employees increases. The log-log regression functions for each sector showed a positive relationship between the number of employees and the total waste generation in tons, with r^2 values between 0.40 and 0.83. This confirms that it is reasonable to assume that the industrial waste generated within each sector is correlated to its number of employees.

Figure 5 illustrates that some sectors generate more waste per employee than others. For example, a company in the paper sector with 1,000 employees is expected to generate around 4,000 tons of waste, while food manufacturing companies are expected to generate around 2,095 tons. Interestingly, the graphs also show that as the number of employees increases, the amount of generated waste per employee tends to increase as well. Using the paper sector as an example, companies with 1,000 employees would generate 4,000 tons of waste, whereas 81,000 tons would be generated by companies with 10,000 employees. This can be explained by the finding that labor productivity grows exponentially at a positive constant rate (Farmer and Schelnast, 2013).

Figure 5 *– Graphs showing Waste Intensity Factors per sector in Europe, per employee (Paper II)*



Once the total amounts of generated wastes have been accounted it is possible to analyze the types of waste expected to be generated. Two options have been investigated in this thesis: Sector Waste Profiles, and Industry Waste Profiles. Figure 6 shows Sector Waste Profiles – expected types of EWC12 waste generated by each sector for each ton of waste, based on data for 2014 for 28 EU countries. Each boxplot represents the share of each waste type that was generated by each industry sector. As an example, within the paper manufacturing sector, non-metallic minerals (category 7 in EWC12) represents approximately 55% of the total waste generated by the sector. Figure 6 shows that some sectors generate mainly one type of waste, while others generate several waste types. Example of the first includes manufacture of wood, which generated mostly wastes from category 7 in EWC12 (between 80 to 95% of the waste). The second type includes manufacture of chemicals, which generated wastes from categories 1, 2, 7, and 10 in EWC12. The finding here is that the manufacture of chemicals sector tends to generate wastes with greater diversity than the manufacture of wood sector. Sector Waste Profiles were also generated for the EWC 42 waste categories (supplementary information Figure 1 in Paper II). The Sector Waste Profiles can be updated on a regular basis, as waste generation data is published every other year.



EWC12 Categories

01 Chemical compound wastes
02 Chemical preparation wastes
03 Other chemical wastes
05 Health care and biological wastes
06 Metallic wastes
07 Non-metallic wastes
08 Discarded equipment
09 Animal and vegetal wastes
10 Mixed ordinary wastes
11 Common sludges
12 Mineral wastes

***Figure 6** – EWC12 Waste Profiles for sectors (2014 data from 24 EU countries) (Paper II)*

The types of wastes generated by different industries were studied using the Industry Waste Ratio Profiles. The main difference between the Sector Waste Ratio Profiles and the Industry Waste Ratio Profiles, is that the latter are more detailed, both in relation to industry types and to waste categories. Figure 7 shows an excerpt of the Industry Waste Ratio (IWR) for industries generating biodegradable waste. In this particular case, it can be expected that EWC42 09.1 (Waste of food preparation products) is being generated by NACE 1011 (Processing and preserving of meat) and NACE 1042 (Manufacture of margarine and similar edible fats) among others. The EWC codes, can also be disaggregated into LoW codes. Therefore, instead of using 42 waste types (EWC-stat), results can be obtained for approximately 800 types of wastes (LoW). Using the same example, it can be expected that the majority of the code EWC42 09.1 in the first case relates to LoW 20202 (animal-tissue waste). In the second case EWC42 09.1 is probably mostly made up of LoW 20201 (sludge from washing and cleaning). This shows how use of the LoW waste category allows more detailed information on wastes to be obtained, however the level of uncertainty is also higher.

Food processing sector

NACE	Descrtiption
1011	Processing and preserving of meat
1012	Processing and preserving of poultry meat
1013	Production of meat and poultry meat products
1020	Processing and preserving of fish, crustaceans and molluscs
1031	Processing and preserving of potatoes
1032	Manufacture of fruit and vegetable juice
1039	Other processing and preserving of fruit and vegetables
1041	Manufacture of oils and fats
1042	Manufacture of margarine and similar edible fats
1051	Operation of dairies and cheese making
1052	Manufacture of ice cream
1061	Manufacture of grain mill products

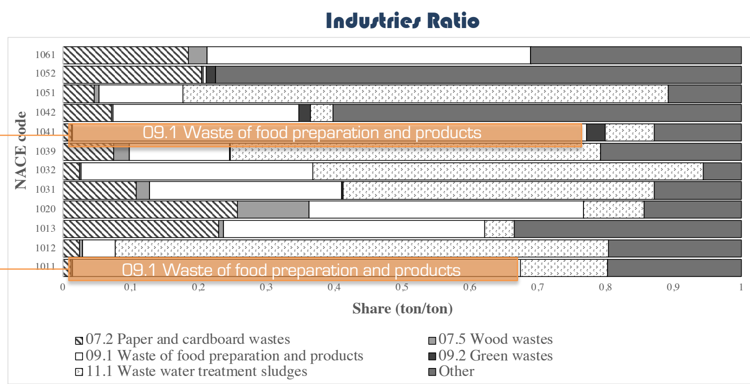


***Figure 7** – Excerpt of Industry Waste Ratio (IWR) for industries generating biodegradable waste (EWC42). Note: none of the NACE industries presented in this figure produce waste belonging to category 9.3, why this category is not included in the figure.*

The generation frequency for different waste types, by industry, is another way to analyze expected waste generation. The heat map in Figure 8 shows the frequency with which waste types (LoW code) are generated within each industry (NACE code). In the heat map, the columns represent industries, and the rows represent types of wastes. Each cell contains a value of 0 to 4. As an example, a frequency value of 2 represents a waste that was generated in 2 of the 4 studied years, by at least one company belonging to a particular industry. The heat map shows that some wastes are generated by all the industries, whereas others are only produced by certain industries. Examples of the former include non-metallic wastes, such as paper and cardboard or plastic wastes, that are generated with high frequency by almost all industries, represented in Box 1. An example of the latter is animal and vegetable wastes, which are mostly generated within the food processing industry, represented in Box 2.

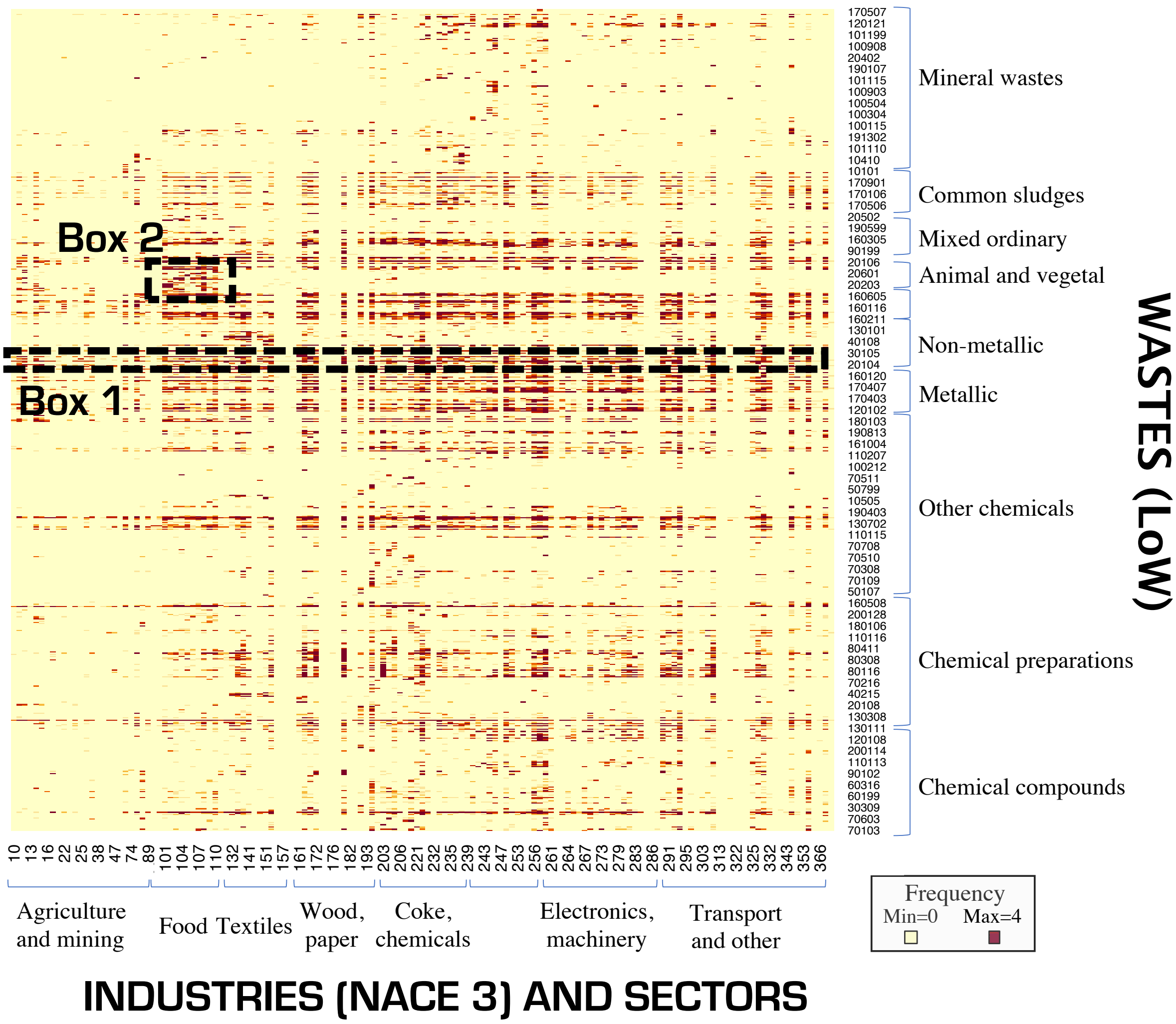


***Figure 8** - Heat map of waste frequencies for each industry (Paper IV)*

Table 2 compares the results obtained from the interviews with companies in the brewery industry (Paper I) with the Waste Frequency database. Twelve waste types, which were generated by almost all the breweries were identified in the interviews. These products were also identified as having a high probability of being produced in the Waste Frequency database, with frequency values of 3 and 4 out of a maximum of 4. In the Waste Frequency database, a total of 38 different LoW codes were identified as having maximum frequency. The larger number may be caused by the fact that some of the wastes can be classified as more than one LoW code. The reason is that some codes cover a broad range of wastes. One example is waste yeast, which can be classified as several LoW codes, including: LoW 20701 (wastes from washing, cleaning and mechanical reduction of raw materials), LoW 20702 (wastes from spirit distillation) or LoW 20704 (materials unsuitable for consumption or processing). Additionally, the Waste Frequency database identifies wastes that may not be have been captured in the interviews, such as engine oils, absorbents, and discarded electrical and electronic equipment. However, in general the wastes identified using the Waste Frequency database were in line with the wastes identified in the interviews.

***Table 2** – Comparison between the information obtained from the Waste Frequency database (Paper II) and the interview results (Paper I)*

Waste Outputs	LoW (Identified manually)	LoW Description	Interview Frequency (out of 5)	Waste Frequency - PT (out of 4)
Spent grain	020799	wastes not otherwise specified	5	4
Yeast/hops	20702	wastes from spirits distillation	5	4
Woven plastic	70213	plastic packaging	5	4
Plastic bags for malt	70213	waste plastic	5	4
Carton	150101	paper and cardboard packaging	5	4
Glass	150107	glass packaging	4	4
Paper	200101	paper and cardboard	4	4
Pallet	150103	wooden packaging	3	4
Caps	200140	metals	5	4
Metal kegs	200140	metals	4	4
Plastic kegs	70213	waste plastic	4	4
Mixed waste	200301	mixed municipal waste	5	4

Note: Examples of other wastes captured with the Waste Frequency database: fluorescent tubes, discarded electrical and electronic equipment, engine oils, and absorbents

In general, information about the amounts and types of wastes generated by industries is very scarce. When available, the data is very aggregated and with a low level of detail (Reynolds et al., 2016). Therefore, the top-down method can play an important role in the estimation of potential wastes generated by industries. Number of employees was shown to be a good and readily available factor for approximation of waste quantities at industry level. The calculated Sector Waste Factor (WF) can therefore be used as a rough estimator of the amounts of waste generated by a sector in a given region, or by an individual company within the sector, assuming that companies from the same sector produce approximately the same quantities of waste per employee. It is important to bear in mind that waste generation intensity is not only related to the number of employees, but also to other factors, such as: environmental policy, legal instruments, economic instruments, enforcement/control, production processes, products, additive environment protection measures, waste prevention, recycling, disposal, logistics, etc. (Mertins et al., 1999). However, with the exception of data on number of employees, data on conditions at the regional level is often not available. Therefore, number of employees can be considered a commonly available data source that can be used to produce a first estimate of the amount of industrial waste expected to be generated by a company or industry.

The results in this section gave insights on a number of possible ways to identify the types of wastes generated by sectors or industries. The applications of this methodology are manifold; it can be used to study e.g. a specific waste flow, a specific sector or industry, or multiple wastes and industries. The results can be used for different purposes, including to define strategies for specific wastes or to track changes in waste generations between years. From an Industrial Symbiosis perspective, this information can be used to identify sources of waste with the potential to replace input materials.

4.2.2 Identification of generic material inputs (Paper III)

Research Question number 3.2 aimed to investigate whether it is possible to identify generic material inputs using a top-down methodology. Paper III introduced a method that identifies common industrial inputs based on International Trade data. This involved analyzing the frequencies at which a material is used by each industry over a 13-year timespan. Table 3 shows an excerpt of the database containing the 130,014 import frequencies for different material inputs for all industries in Sweden. Each number represents the frequency at which a material was imported by an industry. For example, materials from category CN 7208 (Flat hot-rolled products of iron or non-allow steel) were imported 13 times by the industries with NACE codes 284 (Forging, pressing, stamping and roll forming of metal; powder metallurgy) and 285 (Treatment and coating of metals; general mechanical engineering). In the database, it was found that 6% of the 130,014 transactions related to materials consumed every year by industries. This information may be valuable for stakeholders wishing to identify potential opportunities for replacing current inputs with available wastes or by-products.

***Table 3** – Excerpt from the Material Inputs Frequency database for Swedish imports, by CN code and industry of destination (Paper III)*

		NACE 3				
		282	283	284	285	286
CN 4	Description	Manufacture of tanks, reservoirs and containers of metal; manufacture of central heating radiators and boilers	Manufacture of steam generators, except central heating hot water boilers	Forging, pressing, stamping and roll forming of metal; powder metallurgy	Treatment and coating of metals; general mechanical engineering	Manufacture of cutlery, tools and general hardware
7207	Semi-finished products of iron or non-alloy steel	4	0	8	13	5
7208	Flat-rolled products of iron or non-alloy steel, of a width >= 600 mm, hot-rolled, not clad, plated or coated	10	3	13	13	11
7209	Flat-rolled products of iron or non-alloy steel, of a width of >= 600 mm, cold-rolled "cold-reduced", not clad, plated or coated	3	0	13	13	6
7210	Flat-rolled products of iron or non-alloy steel, of a width >= 600 mm, hot-rolled or cold-rolled "cold-reduced", clad, plated or coated	4	1	13	13	1
7211	Flat-rolled products of iron or non-alloy steel, of a width of < 600 mm, hot-rolled or cold-rolled "cold-reduced", not clad, plated or coated	6	0	13	13	13
8402	Steam or other vapour generating boilers; superheated water boilers; parts thereof	11	13	0	4	4

To verify the obtained frequencies, the results were compared with 2 other databases containing data on Portuguese Imports and Swedish Exports, respectively. When compared, similarities of 60–80% for the frequency values of corresponding input types were found in all three databases. For exports, transactions relating to several countries are recorded, as goods are exported to multiple countries all over the world. Additionally, when considering only inputs with the maximum frequency of 13, similarities of 57 to 80% were found in the three databases. Based on the frequency data for a given product used by an industry, it can be concluded that companies operating within the same industry tend to use approximately the same material inputs.

In addition to the cross comparison between countries, the frequency results were compared to the material inputs data collected as a part of a bottom-up approach in Paper I (Table 4). The interviews identified 24 material inputs used in beer production. Of these, 14 were products used by all the 5 interviewed breweries. These 14 products also returned the maximum frequency value (13 of 13) in the Material Inputs Frequency database for Sweden. In total, the Swedish Material Inputs Frequency database captured 70 products used on a regular basis by breweries (NACE code 159). The reason why there are more products captured in the Material Inputs Frequency database, is that the method also captures auxiliary products used by this industry. These include inputs such as books, furniture, specialist clothing, plastic tubes, etc. Therefore, it can be concluded that the information obtained in the Material Inputs Frequency database is reliable and can be even more detailed than the data obtained with the bottom-up method.

Table 4 *– Comparison between results obtained from the Material Inputs Frequency database (Paper II) and the interviews (Paper I)*

Material Inputs	CN code (Identified manually)	Interview Frequency (out of 5)	Material Inputs Frequency - SE IMP (out of 13)	Material Inputs Frequency - PT IMP (out of 13)
Barley and Malt	1003 + 1107	5	13	13
Hops	1302	5	13	13
Yeast	2102	5	13	13
Water adjustment, formic acid	2915	2	4	3
Lye	2815	5	9	4
Methanesulfonic acid	2904	1	0	0
Nitric acid	2808	1	0	1
Peracetic acid	2915	1	4	3
Chlorine	2801	1	0	5
Filter		1		
Caps	8309	4	13	13
Bottles	7010	5	13	13
Labels	4821	5	13	13
Flavours e.g. coffee, orange, honey	3302	2	13	13
Cartons	4819	4	13	13
Plastic kegs	3923	4	13	13
Metal kegs	7612	1	13	13
Carbonic acid	2924	5	10	5

Note: Examples of other input materials captured with the Material Inputs Frequency database: Glassware of a kind used for tables, Enzymes, Dishwashing machines, Refrigerators, Tubes, pipes and hoses, Aluminum foil, Books, etc.

The study also calculated the amount of each input, in relation to the total product mass within each industry, defined as Weight Fraction Database. Table 5 shows an excerpt from the Weight Fraction database, with average ratios of product imports by industry in Sweden (using Swedish Imports). The example shows that, on average, CN code 7208 represents over 20% of the total weight of products imported by NACE 285 over the 13 years. The information available in the Weight Fraction database may be very useful in the identification of IS partnerships. As an example, the Material Inputs Frequency database can be used to perform an initial screening to identify industries that may be able to receive a given waste being generated in a region. This can be done by matching the waste to the input that it may be able to replace.

***Table 5 -** Excerpt from the Weight Fraction database by 4-digit CN codes and destination industries for Sweden (Paper III)*

		NACE 3				
		282	283	284	285	286
CN 4	Description	Manufacture of tanks, reservoirs and containers of metal; manufacture of central heating radiators and boilers	Manufacture of steam generators, except central heating hot water boilers	Forging, pressing, stamping and roll forming of metal; powder metallurgy	Treatment and coating of metals; general mechanical engineering	Manufacture of cutlery, tools and general hardware
7207	Semi-finished products of iron or non-alloy steel	0%	0%	4%	2%	0%
7208	Flat-rolled products of iron or non-alloy steel, of a width >= 600 mm, hot-rolled, not clad, plated or coated	1%	0%	11%	7%	0%
7209	Flat-rolled products of iron or non-alloy steel, of a width of >= 600 mm, cold-rolled "cold-reduced", not clad, plated or coated	0%	0%	19%	5%	0%
7210	Flat-rolled products of iron or non-alloy steel, of a width >= 600 mm, hot-rolled or cold-rolled "cold-reduced", clad, plated or coated	0%	0%	20%	31%	0%
7211	Flat-rolled products of iron or non-alloy steel, of a width of < 600 mm, hot-rolled or cold-rolled "cold-reduced", not clad, plated or coated	0%	0%	0%	2%	11%
8402	Steam or other vapour generating boilers; superheated water boilers; parts thereof	1%	9%	0%	0%	0%

The Weight Fraction database produced using data for Sweden was compared to the corresponding database produced using Portuguese data in order to evaluate the potential use of these results for other countries. The results showed that for 4-digit CN codes, few industries have high similarities in their demand patterns. However, the similarities are greater in the analysis for 2-digit CN codes, with cosine similarity coefficients above 0.4 for more than 81% of the industries. This phenomenon can be explained by the minor differences between the 4-digit CN types of inputs used in industrial processes in the two countries, but that the products generally belong to the same 2-digit CN code. As an example, the iron and steel used by NACE 284 in Portugal mostly belong to CN codes 7211 and 7214, while in Sweden, CN codes 7228 and 7210 are more commonly used.

In conclusion, International Trade data can play an important role by indicating the types of materials that different industries can be expected to use. The Material Inputs Frequency database showed that there are many similarities between the material inputs to different industries, even when different countries were compared. It can therefore be assumed that industries of the same type typically need the same types of materials. This information can be of use for multiple applications, including identification of industries that require a given material input. In relation to Industrial Symbiosis, the Material Input Frequency can be used to identify industries that need a particular waste. Regarding the Weight Fraction database, this study discovered that this is more dependent on the country of reference. This may be explained by the fact, that the Weight Fraction database is more dependent on the domestic material inputs available in each country. Nevertheless, the Weight Fraction database gives good insights on which materials inputs are expected to be more needed by industries.

Sections 4.2.1 and 4.2.2 present two methods developed to identify types of wastes and industrial inputs from a top-down perspective. To identify IS opportunities, a matchmaking process must then be carried out to link the types of wastes generated by industries to potential material inputs.

4.2.3 Matching of wastes to material inputs (Paper V)

This section investigates the possibility of matching generated wastes to required material inputs (Research Question number 3.3). This was performed by linking the Waste Frequency and Material Inputs Frequency databases presented in Section 4.2.1 and 4.2.2, respectively, using case studies from the MAESTRI database. After applying the methodology, 158 IS case studies from the MAESTRI database were expanded into 96,622 potential IS matches, which were stored in the Matches database. These matches covered a total of 67 waste types and 80 material input types, divided between 115 Donor industries and 112 Receiver industries, respectively. Table 6 shows an excerpt of the Matches database. The Matches database contains the match ID, the potential Donor industry (NACE), the waste that may be exchanged (LoW) and its corresponding frequency value, the Material Input that the waste may replace (CN) and its corresponding frequency value, and the potential Receiver industry (NACE).

Table 6 - *Excerpt from the Matches database*

Match ID	Donor (NACE)	Waste (LoW)	Waste Frequency	Material Input (CN)	Material Input Frequency	Receiver (NACE)
4450	161	30105	4/4	4401	12/13	014
4451	161	30105	4/4	4401	13/13	162
4452	161	30105	4/4	4401	12/13	171
4453	161	30105	4/4	4401	10/13	201
4887	310	30105	4/4	4401	12/13	014
4888	310	30105	4/4	4401	13/13	162
4889	310	30105	4/4	4401	12/13	171
4890	310	30105	4/4	4401	10/13	201

Table 7 shows a summary of the matches between wastes and material inputs. Each row represents a group of wastes, matched to a group of material inputs, presented in columns. As an example, one of the numbers in the wood waste group refers to a sawmill industry, which generates sawdust. This sawdust could be used as wood particles by industries that produce plywood. This is one example selected from the 7,595 matches, and highlighted with a red box. Note that a cell may contain a repeated Waste – Material Input relation, but the industries must be different. Donors, Wastes, Material Inputs, and Receivers are all assigned a unique code. Additionally, each match provides information on the corresponding frequency. Taking the same example, sawdust is a waste generated 4 out of 4 times by sawmilling industries, and wood particles has a frequency of 13 out of 13 as a material input for industries that produce plywood.

In Table 7, it can be observed that combustion waste is the most prevalent waste group, with a total of 28,532 identified matches. The majority of the combustion wastes are matched to industries that can use this waste as cement-based materials. The second most representative matches are found in the plastic wastes group. In this case, the wastes would replace plastic raw materials as well as textile articles. However, it is important to keep in mind, that the table contains all potential matches, regardless of their frequency values. On the one hand, it includes wastes with high frequency values, indicating that there is a high probability that an industry generates the waste in question, or that an industry uses it as raw material. The table also includes low frequency values, which indicate that a waste is less likely to be generated or used by an industry.

Both the Waste Frequency database and the Material Inputs Frequency database can be of great use to identify potential matches between industries. When linked together, available IS case studies can be expanded into multiple relations between potential Donors and Receivers. Additionally, the number of matches can be easily expanded if other IS databases or individual industrial case studies are used. The process is computerized using a code that enables fast execution. If applied to spatial analysis, these matches are further converted into actual potential opportunities for IS partnerships between specific companies. In the following sections, examples of three case studies are presented and explored.

Table 7 *– Potential Matches between Wastes and Material Inputs (Paper V)*

	Meat and edible meat offal	Oil seeds and oleaginous fruits;	Lac; gums, resins and other vegetable saps and extracts	Vegetable plaiting materials;	Sugars and sugar confectionery	prepared animal fodder; residues	plastering materials, lime and cement	Ores, slag and ash	Mineral fuels, mineral oils and products of their distillation;	Inorganic chemicals;	Organic chemicals	Fertilisers	Albuminoidal substances; modified starches; glues; enzymes	Miscellaneous chemical products	Plastics and articles thereof	Wood and articles of wood; wood charcoal	Pulp of wood or of other fibrous cellulosic material;	Silk	Wool, fine or coarse animal hair;	Cotton	Man-made staple fibres	Other made-up textile articles;	Articles of stone, plaster, cement, asbestos, mica or similar materials	Other base metals; cermets;	Electrical machinery and equipment and parts thereof;
EWC / CN Groups	**2**	**12**	**13**	**14**	**17**	**23**	**25**	**26**	**27**	**28**	**29**	**31**	**35**	**38**	**39**	**44**	**47**	**50**	**51**	**52**	**55**	**63**	**68**	**81**	**85**
01.1 Spent solvents											5358			595											
01.2 Acid, alkaline or saline wastes							52			8826		34													
02.1 Off-specification chemical wastes							92			168			1005												
02.3 Mixed chemical wastes											1026														
03.1 Chemical deposits and residues												27											2233		
03.2 Industrial effluent sludges						36	87			42		54													
06.1 Ferrous metal waste and scrap										144															
07.2 Paper and cardboard wastes																	555								
07.4 Plastic wastes															7848							5995			
07.5 Wood wastes																$\boxed{7594}$	1680								
07.6 Textile wastes																		288	288	864	720	790			
08.4 Discarded machines and equipment components																									8800
09.1 Waste of food preparation and products	145	120	48		20	3084	87					2862													
09.2 Green wastes																480									
09.3 Slurry and manure				213																					
10.2 Mixed and undifferentiated materials							418					135													
11.1 Waste water treatment sludges												162													
11.2 Sludges from purification of drinking and process water												378		245											
12.1 Construction and demolition wastes														3740											
12.3 Waste of naturally occurring minerals							459		138																
12.4 Combustion wastes							4782	10	140															23600	
12.5 Various mineral wastes										100				55											

4.3 Top-down methodology application

This section shows three examples of application of the top-down methodology.

4.3.1 Wood waste application (Paper IV)

Potential IS partnerships in which sawdust could be used as a raw material were identified. This was performed by combining the information generated from the top-down methodology with the database of companies operating in the Västra Götaland Region. In total 6,726,534 potential IS links between actual companies were identified. These links take into account all potential relations between all industries within the Västra Götaland Region, without any restrictions. The links were obtained using a single MAESTRI case study. Additionally, multiple potential sawdust applications were identified, including: 1) as a bedding material for animals; 2) as an absorbent material; or, 3) as a fuel source (see table 5 in Paper IV for further uses and descriptions).

The first criterion to be applied was a maximum distance between potential Donors and Receivers of the sawdust, which was set to 47 km. It is well known that geographic proximity between companies maybe be seen as facilitator of IS partnerships (Neves et al., 2019; Simboli et al., 2019). Once the distance limit had been applied, the number of potential links decreased to 1,256,992. This shows that using distance as a criterion provides a fast and easy way to perform an initial screening of potential IS partnerships. It identifies companies that are close to each other, thereby theoretically with a higher potential to be connected in a symbiotic partnership. The defined distance can be modified if no potential partnerships are found.

The second criterion introduced minimum frequency values both for Waste Outputs and Material Inputs. This prioritization step allowed the identification of companies that are more likely to generate sawdust, as well as those more likely to be able to receive it as a raw material. By applying the frequency restrictions (minimum of 3 out of 4 for wastes and minimum of 11 out of 14 for material inputs), the number of matches were reduced to 159,630 potential symbiotic links. Figure 9 shows the potential IS links after the restrictions have been applied. The map includes a total of 1,253 sawdust potential Donors and 233 Receivers. It is important to note that even after applying the criteria, all Donors still had at least one link to a potential Receiver.

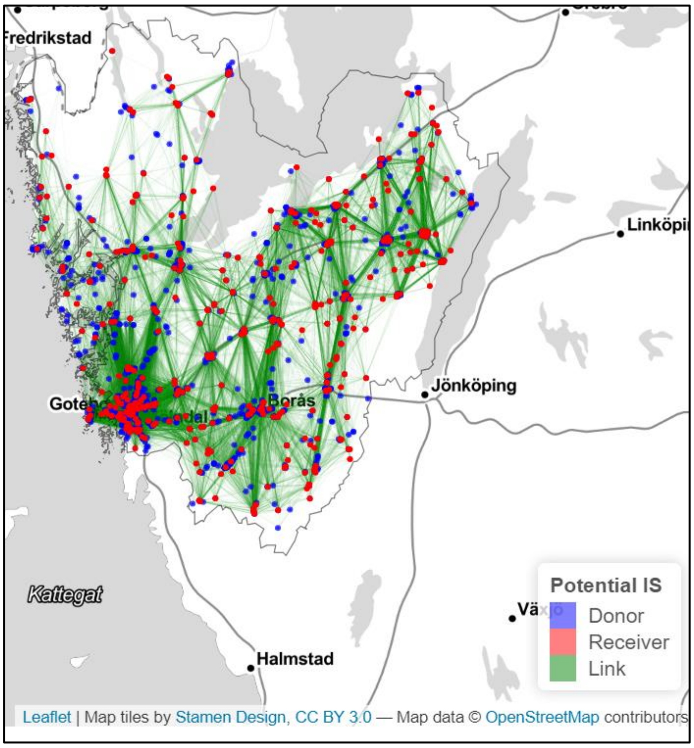


Figure 9 *– Map of obtained potential IS links for sawdust using the matchmaking process presented in this thesis (Paper IV)*

This section presents a short example of the method being applied. A very large number of links was obtained, and it therefore became necessary to apply more tools to further analyze and select the most promising links. As described previously, the large amount of data obtained using top-down approaches, and the difficulty in analyzing such data, are some of the drawbacks of this methodology. The results can be further analyzed, for instance by more detailed investigation into the relations between Donor and Receiver types, as performed in Paper IV. Multiple criteria can be added to select the most promising IS links for further study. As an example, the amount of wastes expected to be generated by each industry can be estimated using the method presented in Section 4.2.1. This is exemplified in the next spatial application. Nevertheless, it is important to bear in mind that the results are potential IS links, and further investigation is required to determine whether they can actually be implemented in reality.

4.3.2 Biogas application (Paper III)

In the biogas case study (Paper V), industries that generate biodegradable waste were matched with biogas producers. Methane yield potential was the first criterion applied, to identify wastes with higher potential for use in biogas production (Table 2 in Paper III). Based on the methane yield potential of each waste type, and the amounts of wastes generated by each industry, the overall methane yield was calculated for each company operating within the Västra Götaland Region (Figure 10). The results showed that the industry generating the waste with the greatest potential for use in biogas production is Manufacture of bread (Table 3 in Paper III). Taking into account all the companies operating in the Region, and assuming that there are no losses, between 0.103 and 0.590 TWh of biogas could be produced annually from industrial waste generated within the Region. The higher value represents approximately 25% of the set target, as defined by the Region for 2020. Additionally, the map shows some of the potential Receivers for the identified waste. Distance between waste producers and potential users was defined as the second criterion for prioritizing potential symbiosis partnerships. Figure 10 presents a heat map with the locations of potential Donors and Receivers of biodegradable waste.

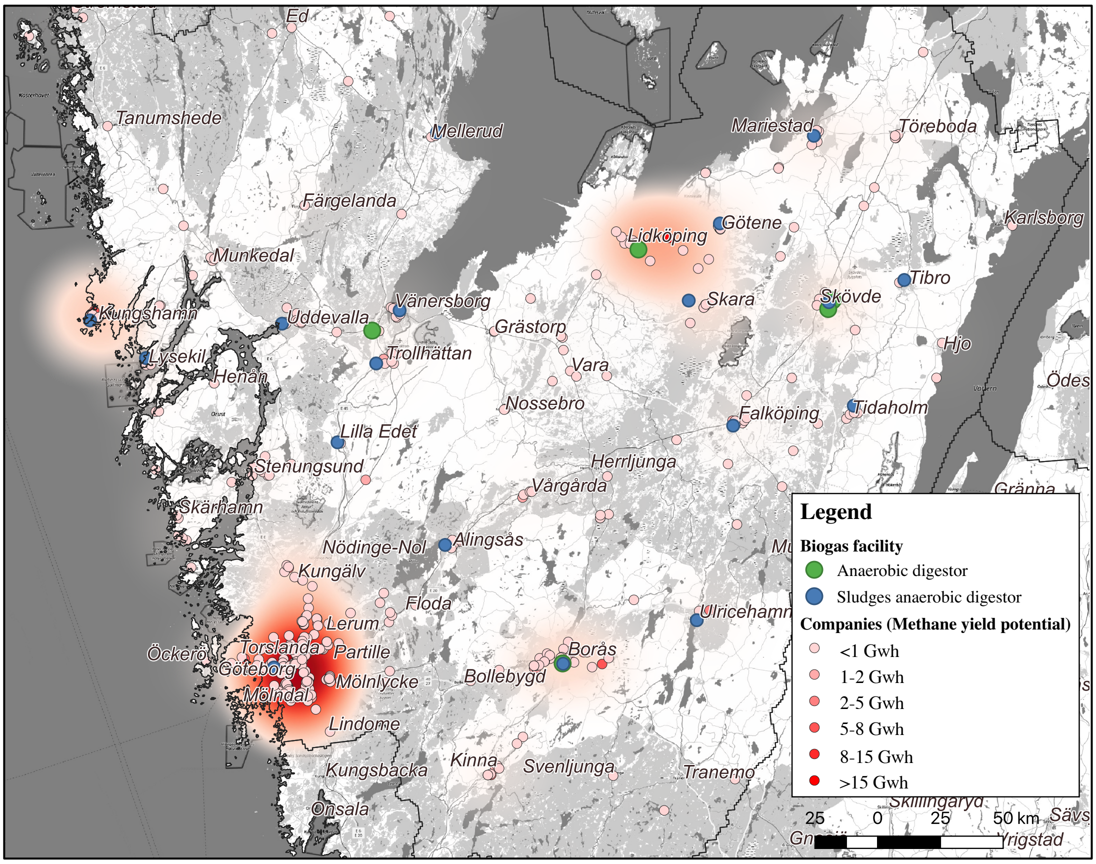


***Figure 10** – Heat map with potential Donors and Receivers of biodegradable industrial waste (Paper II)*

In this case study, the applied criteria enabled the selection of industries that generate wastes expected to have higher methane content. These are the companies assumed to generate wastes with a higher potential for biogas production. In comparison to the first case study, the use of expected waste quantities allowed better prioritization of potential industry Donors. Additionally, by estimating the amounts of methane that will be generated, a comparison with the biogas production targets for the Region was possible.

4.3.3 Carbon capture and utilization (Paper V)

Paper V applies a top-down approach to identify IS opportunities within carbon capture and utilization (CCU) by matching potential CO_2 Donors to CO_2 Receivers. In likeness with the previous spatial analyses, this analysis also used pre-defined criteria to select the most promising opportunities. CO_2 quantities and purity were selected as primary criteria. Figure 11 shows the identified CO_2 point sources in the Region, categorized according to their CO_2 magnitude and purity. In 2012, approximately 6.6 Mtons of CO_2 were emitted in the case-study Region, by 65 facilities in different industries. The majority of the CO_2 emissions originated from CO_2 point sources with a CO_2 concentration below 20%, such as industries within the energy sector and oil refineries. A few sources of high purity CO_2 were identified, in particular 13 biogas purification plants and an ethylene-oxide (EO) plant. These sources would be attractive for CO_2 reuse; however, the magnitudes were still low compared to the other sources. Although high purity sources are very attractive for carbon capture, they actually only represent 2% of the CO_2 point sources in the world (Naims, 2016).

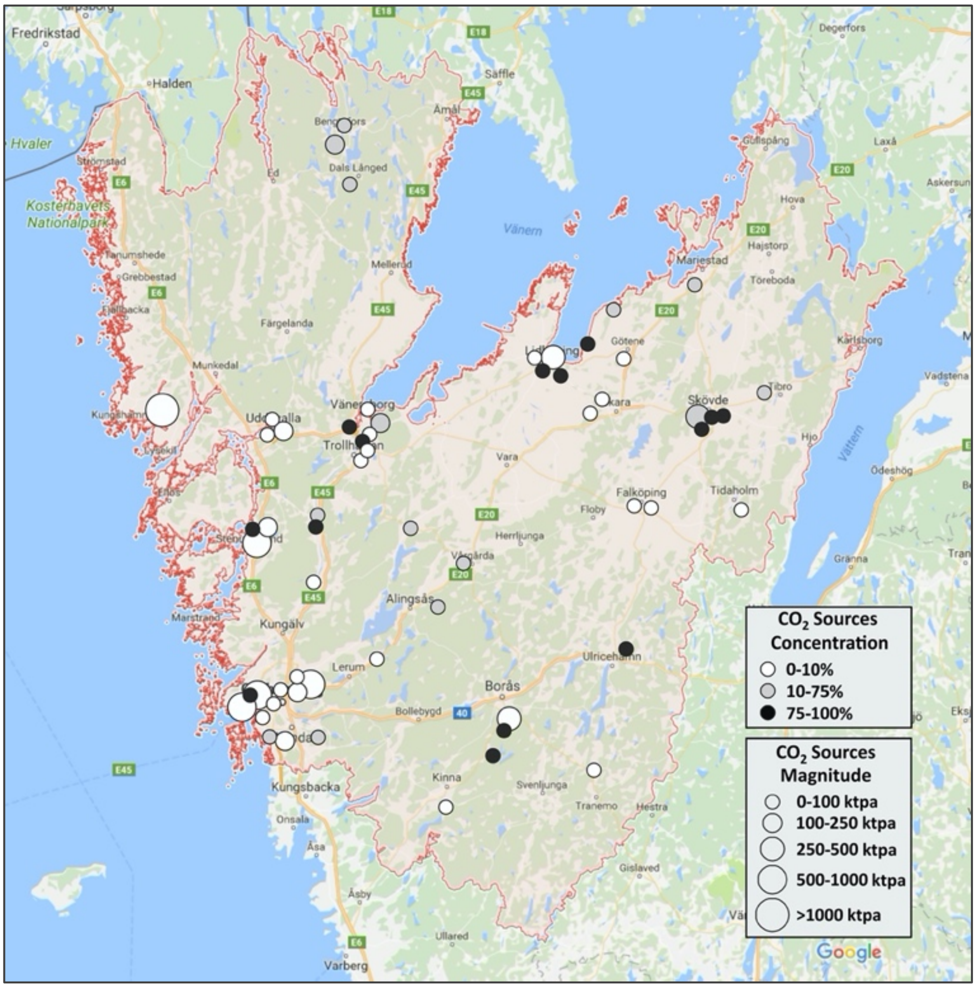


Figure 11 - *CO_2 sources according to purity and magnitude (Paper IV)*

Regarding CO_2 utilization technologies, nine out of seventeen options were selected as good candidates for implementation in the Region. The excluded Receivers were dependent on the existence of a specific infrastructure or industries not currently present in the area, namely, red mud carbonation, sugar production, water desalination, urea yield boosting, enhanced oil recovery, or enhanced coal bed methane recovery. The selected Receivers were divided into two different groups. The first group consisted of Receivers currently operating in the Region that may use CO_2 in their industrial processes; processes included mineral carbonation, concrete curing, polymer processing, lignin production, and pH control. The second group contained potential opportunities for new Receivers or new businesses, such as algae production, methanol production, and power-to-gas. Table 3 presents a summary of the main results obtained for each of the studied Receivers. The table includes the industrial process, a short description of each of the technologies, the type of industry that would use the selected technology, the CO_2 emitter that would be most appropriate for the selected Receiver, some advantages of using the technology, the amount of CO_2 that would be required, and finally a visualization of the symbiotic scheme.

The companies that could be involved in each of the identified IS partnerships were mapped using GIS software (Figure 12). This procedure was performed to take into account an additional criterion, in this case the geographic proximity between CO_2 producer and potential CO_2 user. This matching process was performed for all the selected potential CCU technologies. To illustrate the process, the obtained results are shown in Figure 12, where a selection of the overall results are shown on a map of the Region. Combining all the different CCU symbiosis options identified five clusters where such partnerships would be easier to develop, including one near the port of Gothenburg and another close to the Stenungsund Industrial Park.

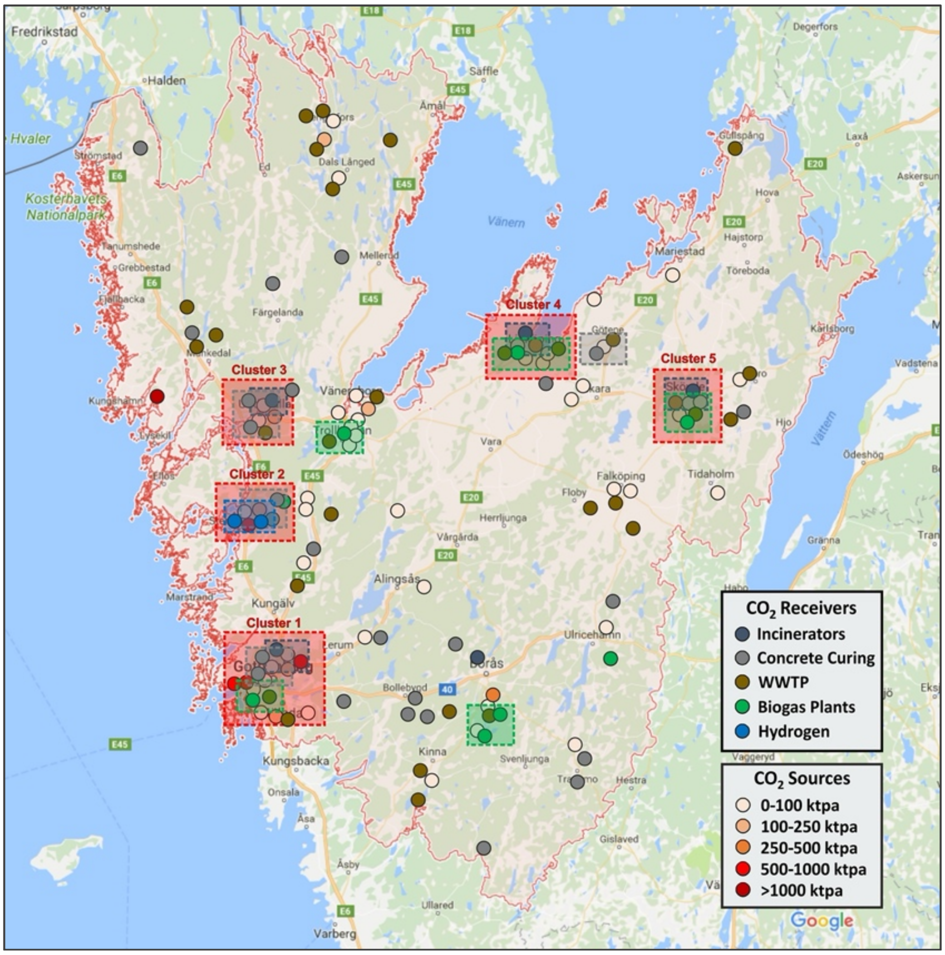
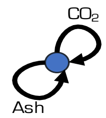
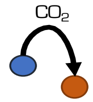
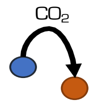
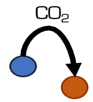
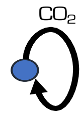
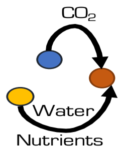
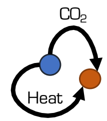
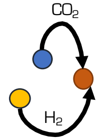
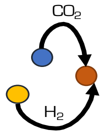


Figure 12 *– Overview of potential CCU symbioses identified in the Västra Götaland Region (Paper IV)*

This case study illustrated the benefits of matching potential CO_2 Donors to potential Receivers. Compared to the previous case studies, additional criteria were added. For the Donors, the CO_2 purity was identified as a useful criterion for selecting sources according to the needs of the Receivers. Additionally, the emitted quantities can also play an important role in the selection. For example, low-volume emitters of high purity CO_2 are perfect sources for Receivers in horticultural production. The Technology Readiness Level (TRL) allowed fast selection of potential Receivers in situations where the intention is to implement an IS partnership in the short to medium term. Finally, the proximity between Donors and Receivers played a very important role in the initial exclusion of links between companies located too far apart. In addition, the availability of auxiliary processes was used as an extra criterion that may facilitate the IS implementation process.

Table 8 *- Technologies for Carbon Capture and utilization with potential to be implemented in Västra Götaland Region*

Industrial Process	Short Description	Potential Receivers	Potential Emitters	Advantages	Potential CO_2 Utilization	Symbiotic Scheme
Mineral Carbonation	Formation of solid carbonate products, based on a reaction between carbon dioxide and alkaline materials composed by calcium and magnesium rich oxides and silicates (Sanna et al., 2014).	.Five waste incinerators (carbonation of the bottom and fly ash); .One steel mill - carbonation of steel slag.	Low purity flue gases with CO_2 concentration of 10% can be used (Lombardi and Carnevale, 2015). In this case, the CO_2 emitted by the incinerators or the steel mill would be the best option.	CO_2 emissions reduction; Reduction of the amount of waste that is currently sent to landfill (ash); Long-term storage of the CO_2; Use of ash to produce construction materials.	In total, approximately 36,000 tCO_2 using steel slag and 23,600 tCO_2 using Municipal Solid Waste ash.	
Concrete Curing	Applied within the curing process or during manufacturing of building products, e.g. building blocks, masonry units, paving stones, cement boards and fibreboards (Shao et al., 2010).	.Thirty-three concrete products industries.	Low purity flue gases with CO_2 concentration of 20% can be used. The closest CO_2 emitter from the concrete products industries would be appropriate.	Long-term storage of the CO_2; Water savings, if water was used in the curing process.	Estimated that 96,000 tons of CO_2 could be used in concrete curing technology.	
pH Control	Carbon dioxide is used worldwide to neutralize alkaline flows in several industries.	.Two drinking water plants.	High pure CO_2 is needed.	Replaces mineral acids.	Already used locally captured CO_2 (approximately 2,000 tCO_2 per year).	
Polymer Synthesis	Utilization of CO_2 as raw material in the polymer. Different polymers can be produced, including Polyurethane or Polycarbonate.	.Five companies that produce polymers in primary forms operating in the region.	Polymer processing requires a highly-concentrated flow of CO_2	Reduce the dependence on petroleum-based materials.	CO_2 needed will depend on the amount and type of polymers that will be produced (from 0.1 to 0.4 tons of CO_2 per ton of polymers produced).	
Lignin Production	Lignin can be extracted from black liquor, a by-product of the pulp mill industry.	.One pulp and paper industry in the region.	Pure CO_2 is necessary. The CO_2 emitted from the pulp and paper industry may be used, after CO_2 has been captured.	The main benefits will be the increase of the production, cost reduction and creation of new sources of income (lignin).	Only one industry may use this technology in the region. No data on amount of pulp produced (confidential).	
Algae production	Cultivation of algae using bioreactors, open pounds or a combination of both systems.	.The algae should be located close to the CO_2 emitter or a wastewater treatment facility.	Low purity flue gases with CO_2 concentration can be used, including flue gases from power stations, refineries or paper industry.	No need for pure CO_2; The large applications of algae; Would be beneficial to get the water from a wastewater treatment plant (rich in nutrients).	Depends on the quantity of algae produced. CO_2 will not be the limiting factor.	
Agricultural Production in Greenhouse Systems	Use of CO_2 in agricultural production. In general, when raising the CO_2 level from ambient values, about 340 ppm to 1,000 ppm, an increase of photosynthesis by around 50% can be obtained (Blom, et al., 2009).	.The greenhouse would be installed close to a biogas upgrading plant, that produces high pure CO_2.	High pure CO_2 is needed.	Could be a source to increase the quantity of agriculture products produced in the region; Heat and CO_2 exchanged at the same time would be the perfect combination.	Depends on the size of the greenhouse. A greenhouse in Sweden needs between 90 and 180 tons of CO_2 per year per ha.	

Industrial Process	Short Description	Potential Receivers	Potential Emitters	Advantages	Potential CO_2 Utilization	Symbiotic Scheme
Methanol Production	Methanol can be produced using CO_2 and H_2 as feedstock. The electrolysis of water produces hydrogen (H_2), which is combined with CO_2, compressed and reacted over a metal/metal oxide catalyst to produce methanol and water ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$).	.H_2 is needed. An alternative would be that the methanol producer would be close to an industry that produces H_2 as by product and a CO_2 high pure source. One symbiotic scheme was identified in the region.	High purity CO_2 is needed; Nearby the H_2 sources, exists a high pure CO_2 source.	Large applications of methanol; Avoids the need to import methanol from international markets.	Considering the available H_2, 63,000 tons of CO_2 would be necessary to produce 45,360 tons of methanol per year, assuming a 100% conversion.	
Power to gas	Power to gas technology focuses on the transformation of electrical energy to SNG (synthetic natural gas), by combining CO_2 with H_2.	H_2 is needed. An alternative would be that the methanol producer would be close to an industry that produces H_2 as by product and a CO_2 high pure source. One symbiotic scheme was identified in the region.	High purity CO_2 is needed; Nearby the H_2 sources, exists a high pure CO_2 source.	Conversion of renewable energy into storable energy (methane).	Considering the available H_2, 66,500 tons of CO_2 would be necessary to produce 24,206 tons of methane per year, assuming a 100% conversion.	

Legend: CO_2 Source; CO_2 Receiver; Auxiliary process

4.4 Implications of the results

The results presented in this thesis have several implications for science and practice, regarding both its methodological contributions and the results of the studies.

4.4.1 Scientific implications

The methodological developments and results of this thesis advance the identification of IS opportunities in different ways. The following paragraphs describe how the methodologies developed in this thesis can overcome some of the identified gaps and challenges.

One of the main advantages of the developed methods, and of top-down approaches in general, is the use of already available and regularly updated databases, which makes it easy to keep the results updated. As an example, the Material Inputs Frequency database can be updated annually, as new international trade data is released. Additionally, the regular updates make it possible to capture changes in the systems being studied, including changes in manufacturing techniques or supply chains. Moreover, the use of already available statistical data helps to overcome confidentiality issues related to data on inputs and waste streams, a common issue according to several authors (Robin, 2016; Tseng et al., 2018)

Chen and Ma (2015) pointed out the need for more comprehensive and well-structured databases of material flows. This issue has been addressed by using standard nomenclatures in the methods developed in this thesis. Material inputs, industries, and wastes have been classified using the taxonomy developed by the European Union. The use of standard nomenclatures enables application of the methods at any spatial scale in Europe. These standard classifications have high levels of disaggregation, which enables studies with different levels of detail. Additionally, there are correspondence tables between the European Union nomenclatures and other worldwide nomenclatures, which makes it possible to adapt methods or results to other geographical areas. As an example, the NACE nomenclature can be related to the North American Industry Classification System (NAICS) (Ramon, 2020).

Tseng et al. (2018) highlighted that there are quantitative tools available to support decision-making processes, but these are focused on single companies or single supply chain systems. The methods developed in this thesis are comprehensive and consider all the types of industries operating within a region. Additionally, they are comprehensive concerning company size. Another advantage is that all industries are considered in parallel. Considering multiple industries at the same time opens greater possibilities to identify potential IS partnerships. This is in line with Jensen (2016), which states that industry diversity may play an important role in the promotion of IS partnerships. Inclusion of different industries brings opportunities to find different types of generated wastes, as well as greater potential to find prospective Waste Receivers. This is exemplified in the first case study (see section 4.1), in which three reuse solutions for spent grain are presented (Figure 4). Considering multiple Waste Receivers increases both the potential number of waste applications and the number of IS partnership opportunities. As stated by the European Commission (European Commission, 2018) there is a need for more tools enabling identification of symbiosis opportunities between different industry sectors.

The developed methods are very versatile. They can be applied at national or regional level, or even to an industrial park. Additionally, the different components of the developed methodologies can be applied separately, depending on the type of study to be performed. For example, the Material Inputs Frequency database (section 4.2.2) and the Waste Frequency database (section 4.2.1) are stand-alone tools with multiple potential applications. Additionally, the applications are not limited to the IS field, as there are other fields in which the methods could be of use. As an example, the method for identification of common material inputs (section 4.2.2) could be applied to enable greening of the supply chain, or to investigate the dependency of different industries on non-renewable materials from a top-down perspective, in order to find renewable substitutes.

4.4.2 Practical implications

The results of this thesis have some implications that are of interest beyond a scientific audience. The results can help e.g. local authorities, regional developers, NGOs, and industrial associations to obtain the data needed to foster Circular Economy implementation in a given region. As an example, the obtained results for the biogas assessment performed in Paper II (see section 4.3.2), were shared with a regional energy agency for the Västra Götaland Region – Hållbar Utveckling Väst. The agency works to promote sustainable development in general, and sustainable energy sources in particular, such as development of a regional biogas structure. In this particular case, the results have shown how biogas generated from industrial sources could help to achieve the defined regional biogas production target of 2.4 TWh per year by 2020 (Västra Götaland Region, 2016).

The developed methodology should be seen as a starting point for identification of IS opportunities. Once stakeholders with the potential to be part of an IS partnership have been identified using the presented methodology, they can be invited to a workshop to evaluate the possibility of progressing the IS opportunity. Other tools, including LCA studies or cost-benefit analyses, can support this assessment by giving a better understanding of potential economic, environmental, and social gains from a specific IS implementation.

One of the examples tested in this thesis was to suggest implementation of innovative CCU technologies at the regional level (section 4.3.3). The implementation of such technologies may help regions to achieve the ambitious targets for CO_2 reduction, as defined by the European Commission, as well as by national and regional authorities. Additionally, the presented CCU technologies can also be seen as new business opportunities to boost the competitiveness of industries. The results can support regional stakeholders in the promotion of IS partnerships. This methodology not only identifies individual companies operating in the Region that may utilize CO_2, but also suggests potential opportunities for new businesses, and offers information on criteria that may aid the implementation of a specific IS partnership.

There is a medium-term plan for implementation of regional centers, under a national center, to support IS partnerships in Sweden (Harris et al., 2018). The plan has highlighted some priority areas to focus on. The development of tools to aid the identification of IS opportunities is one of these focus areas. Methods like the ones developed in this thesis can help to achieve this by facilitating IS identification, both at the national and regional scale. Additionally, the (Harris et al., 2018) document identifies as a critical element the alignment of IS across different sectors. This highlights the importance of considering a variety of industries when IS opportunities are being identified, as pointed out above in the section on scientific implications. This reinforces the importance of having tools, such as the one developed in this thesis, with a comprehensive approach to industries, wastes, and material inputs.

5 CONCLUSIONS

The objective of this thesis was to contribute to the field of Industrial Symbiosis development, with focus on identifying opportunities for Industrial Symbiosis from a top-down perspective. Moreover, this thesis presents a methodology that maps potential IS opportunities without requiring prior contacts with companies. This is achieved by using available statistical data sources. In the following paragraphs, the main findings of this work are described.

In the first study, IS practices by companies from two different industries were studied. Interviews confirmed that most companies need external support to become engaged in IS partnerships. Companies typically face the same issues when adopting IS practices, namely lack of time, lack of knowledge, or difficulty in finding an IS partner. This indicates that facilitation entities need to support companies, both in the identification of potential IS partnerships and in implementing them. Nevertheless, it was also observed that some companies already engage in IS, mainly due to the clear benefits of cost reductions and the opportunity to improve environmental performance.

The types of methods that can be used to identify potential opportunities for IS partnerships depend significantly on the number of companies included in the study. With bottom-up approaches, the results are generally more accurate, but the identification process can be time-consuming. Top-down approaches are faster to implement and able to give good indications of potential IS opportunities. As a conclusion, bottom-up approaches are more appropriate for studies with a small number of companies, while top-down approaches should be applied to studies covering a larger number of companies.

Finding detailed data on wastes generated by industries is a challenging process. Waste data is mostly available at a highly aggregated level, both in relation to waste and industry type. However, this thesis has identified a positive correlation between the number of employees and amounts of wastes generated by industry sectors. Data on employee numbers is easily accessible and can give a good indication of the amounts of wastes that can be expected. Furthermore, it was observed that there are patterns in the generation of wastes by industrial sectors. This means that industry sectors generated approximately the same waste types. The analysis of wastes generated by industries was more limited due to the lack of available data. However, by building Waste Frequency databases, a good indication on the types of wastes that are likely to be generated within each industry can be provided.

Material inputs needs for industries can be studied and analyzed using International Trade data. The Material Inputs Frequency database showed that there are patterns for the types of materials used by each industry. When three different databases were compared, similarities of 60–80% were obtained for the frequency values of the same input types within their processes. This database is easy and fast to build and can be used to identify potential uses for the wastes generated in a given area. To build a database containing the share of the materials used by each industry is also possible, by using the Weight Fraction database. However, this database will mostly provide an indication of the main shares of imported goods for each industry, and will not include domestically produced inputs.

It was shown in this thesis that it is possible to link wastes to material inputs. The links can be identified with systematic approaches, e.g. by using the MAESTRI database. By identifying potential sources of waste and potential destinations for material inputs, IS case studies can be expanded to provide multiple potential IS links. As an example, 158 IS cases from the MAESTRI database were expanded into 96,622 matches for potential IS partnerships, which were stored in the Matches database. The Matches database contains the frequency values obtained from the Waste Frequency and Material Inputs Frequency databases. Because of the taxonomy used in the Matches database, it can be used to map potential IS partnerships in a given industrial park, municipality, region, or country.

Finally, the methodology was applied to three case studies that identify potential industrial symbiosis for wood wastes, biogas production and Carbon Capture and Utilization. Additionally, different criteria were applied to prioritize the obtained potential IS partnerships. Frequency values for both wastes and materials inputs are among the used criteria. The frequency values are an attribute available in the Matches database enabling easy and fast initial selection of IS opportunities. The distance between Donors and Receivers was a criterion used within all the case studies. An example from the results of the biogas case study was that if the identified IS opportunities were to be implemented, 0.590TWh of biogas could be generated, representing 25% of the biogas targets set for the Västra Götaland Region. In the carbon utilization case study, 7 technologies with large potential to be implemented in the Region were identified. If these technologies were to be implemented, around 250,000 tCO_2 could be reutilized.

6 OUTLOOK

The work presented in this thesis introduces several aspects concerning identification of IS opportunities. The developed top-down methodology can be seen as groundwork, providing different possibilities for future research.

The Waste and Material Inputs Frequency databases, as presented in Paper II and III, can be further developed. This can be done by studying, analyzing, and comparing additional waste and material input datasets, in order to identify similarities and differences in the wastes and material inputs generated or used in different parts of the world. In relation to this aspect, material input requirements in weight need further study. For now, the material inputs are based on International Trade data, but inputs of domestic materials could also be included, through the use of industrial production datasets and domestic extraction data.

Including the required quantities of different materials would be an important step towards improving the link between generated wastes and material inputs. This is closely related to one of the potential future research topics; how to optimize the identified IS links by taking into account the weight of the generated waste, and the weight of the material inputs needed by companies.

The Matches database, as presented in section 4.2.3, needs to be expanded by considering other IS databases, such as IS-Data (IS Data, 2020). Like the MAESTRI database, IS-Data is a database which compiles IS case studies from around the world. Additionally, the Matches database could be extended by manual introduction of links between wastes and material inputs, learned from different case studies.

Additional criteria that can be applied to the Matches database should also be explored. Environmental, economic, and social benefits are examples of criteria that could help the prioritization of potential IS partnerships. For example, it is well known that economic gain is one of the main drivers for IS implementation (Zhang et al., 2015). Analyses could be performed by coupling other tools to the top-down methodology, such as Cost-Benefit Analysis, Multi-Criteria Decision Analysis, or Life Cycle Assessment.

From a practical perspective, future research could investigate the best strategies for sharing the obtained results with IS facilitators. The same applies to the best ways to use the results in the implementation of IS. One possibility may be to bring the identified companies together in meetings to discuss the identified potential IS partnership, and introduce some preliminary ideas on the advantages and technical details of the identified symbiosis. In some cases, several meetings involving the relevant stakeholders have already been held as part of the work on this thesis; examples include the carbon utilization symbiosis for methanol production, horticulture production, and the mineral carbonation process.

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